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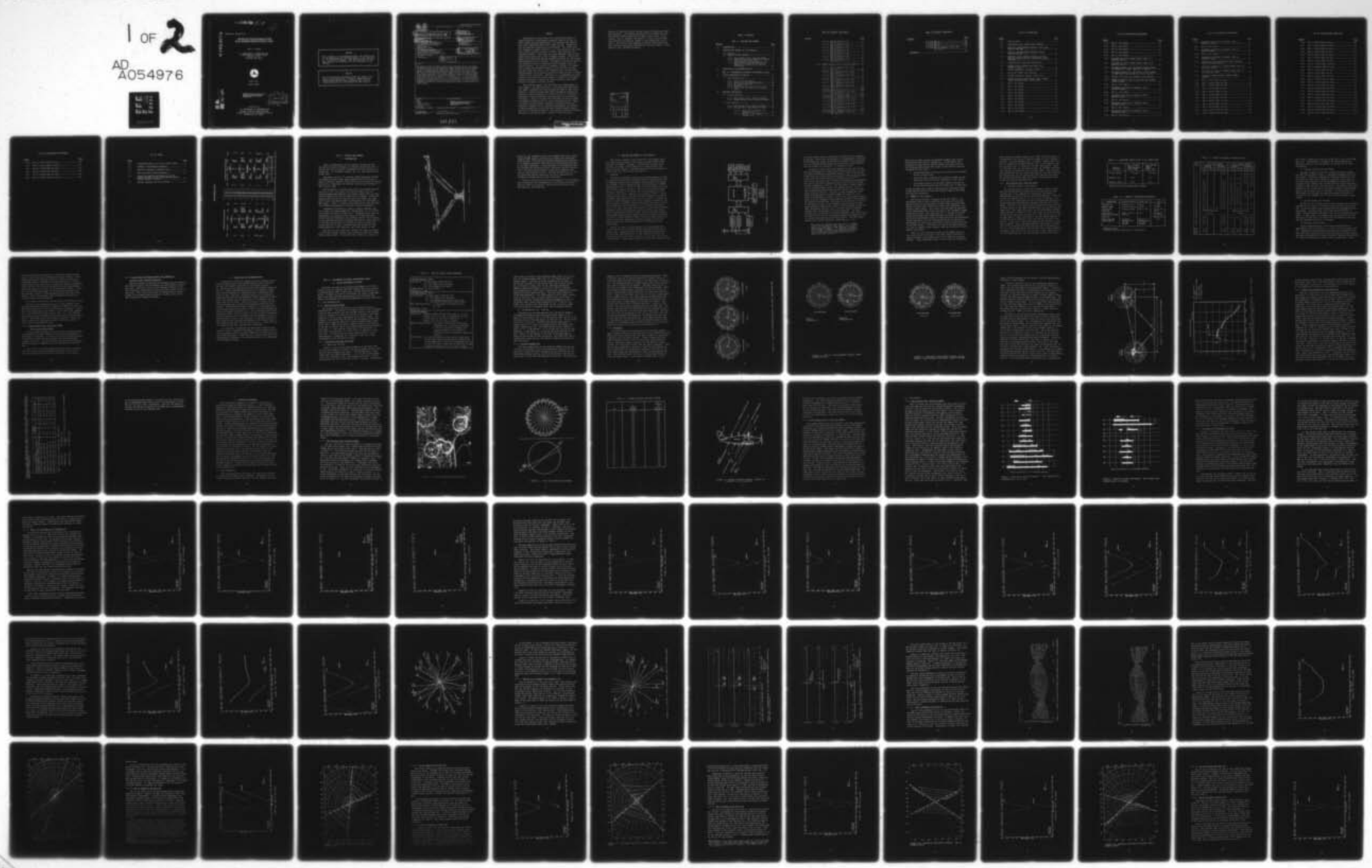

REPORT NO. FAA-RD-78-2

BEACON COLLISION AVOIDANCE SYSTEM (BCAS) AIRBORNE ANTENNA DIVERSITY STUDY

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APRIL 1978

FINAL REPORT

Prepared for

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16. Abstract

The potential need for antenna diversity on the intruding aircraft was examined. The BCAS system was used for determining airborne antenna diversity requirements for general aviation aircraft approaching a BCAS equipped aircraft from various angles. The BCAS system was operated in the forced active plus passive mode. Air Traffic Control Radar Beacon System (ATCRBS) replies to the BCAS interrogator (forced active mode) and to a secondary surveillance radar, SSR (passive mode), were recorded and used as a measure of the adequacy of the air-to-air and ground-to-air radio links for some selected critical situations. The intruding general aviation aircraft was equipped with top - and bottom-mounted ATCRBS antennas (with independent transponders) during one series of encounters. The second series of encounters was flown with an aircraft equipped with a single bottom-mounted transponder antenna.

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PREFACE

The objective of this study is to answer the question--is antenna diversity a requirement on general aviation aircraft in order to make the BCAS operational? Two resources were used for this study; published material and filght testing. Information form the published materials was inconclusive. The flight tests were conducted to answer specifics; i.e., the coverage in the situation in which the BCAS aircraft is flying 2,500 feet above the intruding aircraft. Two flight tests were conducted using a small general aviation aircraft as the intruding aircraft. One test was flown using a Beechcraft Bonanza equipped with both top- and bottom-mounted antennas as the intruder. The replies from the top antenna were delayed to permit a comparison of the tracking of the two received signals. The second test employed a Cessna 172 equipped with a single botton-mounted antenna as the intruding aircraft. From the flight test data, it was concluded that a single botton-mounted antenna for the general aviation aircraft may pose a problem to BCAS in some situations. Therefore, it is recommended that more complete tests involving various degrees of detection difficulties should be conducted to answer the antenna diversity requirement question for general aviation aircraft.

The following agencies and individuals are acknowledged for their support. The National Aviation Facilities Experimental Center, NAFEC, conducted the flight testing described in this report. Theodore J. Turnock provided much needed engineering support and William R. Gadow coordinated the flight activities. Gratitude is expressed to Lincoln Laboratory and especially to the following individuals. Paul R. Drouilhet made available the Lincoln Laboratory Beechcraft Bonanza with its pilot Richard Kalustian. Albert R. Paradis provided helpful information concerning the Lincoln Laboratory L-band air-to-air multipath measurements, and Patricia H. Mann provided the Lincoln Laboratory antenna pattern measurements for the Beechcraft Bonanza. The support of DOT and contractor personnel is also appreciated. Richard F. Bock and Owen E.

McIntire of SRDS-250 provided overall support in making the flight tests possible. John Brennan reviewed the entire manuscript and made several helpful suggestions to improve its clarity. Janis Vilcans, Juris G. Raudseps, and Herbert J. Glynn of TSC provided data reduction and technical support in the preparation of this report. ADP services were supplied by Kentron International Ltd. Data reduction and plotting programs were written by Barry J. Fink, Henrik O. Lind, and Ronit Procaccia.

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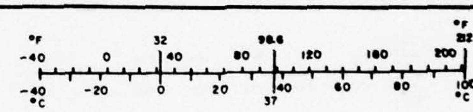
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PART I: OVERVIEW AND SUMMARY

I. INTRODUCTION

There is disagreement over the adequacy of coverage from top and bottom-mounted antennas for general aviation aircraft. To resolve this issue, technical information from two resources was considered: (a) published reports, and (b) data obtained from flight tests.

The purpose herein is to evaluate ATCRBS transponder antenna performance on small single engine general aviation aircraft in order to determine whether antenna diversity on the general aviation aircraft is a requirement for reliable detection and tracking by a BCAS aircraft (OWN).

BCAS operation in a purely passive mode is dependent upon the detection of both the ground interrogation signals from the several ground-based Secondary Surveillance Radars (SSR) and their elicited replies from the intruding aircraft (OTHER). Active mode operation does not involve the SSR radars and depends only upon the RF links from OWN and OTHER (interrogation) and from OTHER to OWN (reply). Figure 1-1 depicts active and passive mode operation. For a detailed description of the BCAS system see Reference 1.

Performance estimates are, however, largely dependent upon one's choice of assumed conditions, and therefore, are of limited value unless verified in flight tests. Estimated values were used nevertheless for guidance in the design of a flight test plan. Flight tests were conducted as an ultimate proof to verify analytical and simulated data and performance predictions. The complexity of the BCAS software made it difficult to predict reliably the system operation in those situations where the various RF links became marginal or fail completely for a short period of time.

The tests for this study were limited to a single test geometry with BCAS flying a 24-petal daisy 2,500 feet above an intruder flying a figure eight. During the single antenna test flight at

BCAS CONCEPTS

PASSIVE/ACTIVE COMBINATION

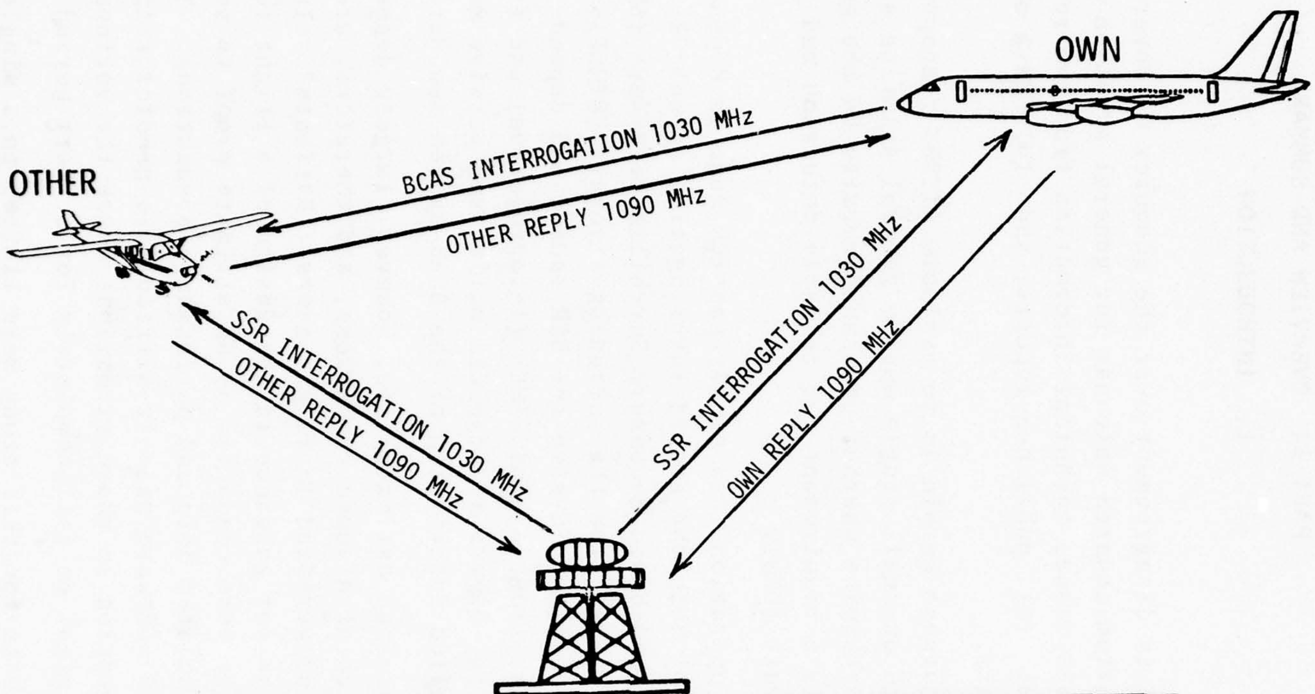


FIGURE 1-1. BCAS RF LINKS

Millville, the intruding aircraft was equipped with only a botton-mounted ATCRBS antenna, and hence no top and bottom comparison could be made. The 2,500 foot altitude separation was selected so as to emphasize potential deficiencies of bottom-mounted antennas in the upper hemisphere. Antenna patterns in two dimensions were not available for the BCAS aircraft, and hence, possible deficiencies in the BCAS antenna patterns could not be separated from those of the intruding aircraft. Possible deficiencies in a top or bottom BCAS antenna pattern may have been compensated for through the antenna diversity used in the BCAS.

Section 2 provides an overview and summary of the test results while conclusions and recommendations are presented in Section 3. Section 4 deals with analysis, and Section 5 with flight tests, data analysis, and evaluation.

2. OVERVIEW AND SUMMARY OF TEST RESULTS

This section presents a brief overview of the antenna diversity question and summarizes the results obtained through flight testing at FAA/NAFEC. Although a significant literature search was made, no attempt will be made here to summarize fully the various reports reviewed. The BCAS concept will be described very briefly here (see, for example, Reference 2).

2.1 OVERVIEW

The BCAS is designed to provide air-derived warnings of threat of collision with any other aircraft within 20 nautical miles that is equipped with an ATCRBS transponder replying with both identity and altitude. BCAS is unique in that, in the presence of ATCRBS ground signals and in the passive mode, BCAS can compute both range and bearing to another aircraft. The use of bearing information permits a reduction of the alarm rate and determination of both horizontal and vertical maneuvers for avoiding a threat. Within ATCRBS coverage, BCAS, using non-directional antennas, listens in on ATCRBS interrogations and their elicited replies. Computations made by on-board equipment, requiring no *a priori* knowledge of the ATC environment, determine range and bearing to the other aircraft. BCAS can operate totally passively if it is within 100 nautical miles of at least two ground radars which are modified with azimuth reference signals indicating and direction of their main beams. BCAS can also measure range to another aircraft directly by generating ATCRBS-compatible interrogations with an on-board transmitter In areas of limited ATCRBS coverage, BCAS may calculate bearing to another aircraft by combining the range measured by the active interrogations with the data obtained by listening in on one ground radar.

Figure 2-1 shows a block diagram of the experimental BCAS system, one version of the BCAS design, which was used during the flight tests. Received signals (replies and SSR interrogations) are processed independently by two dual-channel receivers; one receiver driven by the BCAS top antenna, and the other by the BCAS bottom antenna. Video signal processing selects the stronger of the

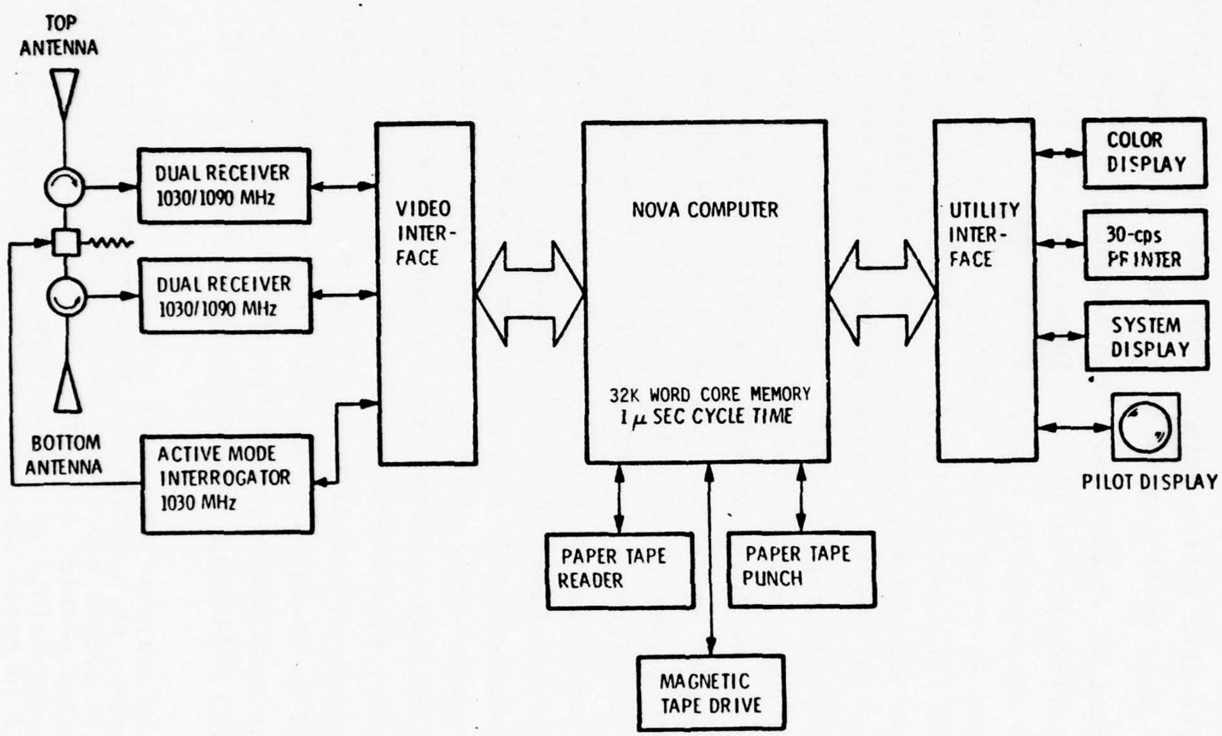


FIGURE 2-1. EXPERIMENTAL BCAS SYSTEM BLOCK DIAGRAM

two reply signals which is converted to digital form for computer processing. Active mode interrogation is accomplished by directing 12 interrogation signals to the BCAS top antenna and 12 interrogations to the BCAS bottom antenna for each burst of interrogations. The active mode burst period is 2.5 seconds per burst.

A number of studies have been conducted in the past to evaluate the performance of various identification friend or foe (IFF) and ATCRBS experimental transponder systems. Many of the earlier flight tests were specifically concerned with the ground-air-ground links in an IFF system carried by a military aircraft.[3,4,5] More recent work by the Navy included an evaluation of experimental portions of the SECANT (Separation Control of Aircraft by Nonsynchronous Techniques) system,[6,7] and the AVOID I (Avionic Observation of Intruder Danger) Collision Avoidance System.[8] Each of these systems employed antenna diversity and was tested on multi-engine military aircraft. FAA tests of dual antenna/dual transponder configurations of standard ATCRBS transponder(s) are reported in References 9 and 10. These tests also employed multi-engine aircraft (Grumman G-159 and Convair CV-880-M) and evaluated the ground-air-ground link. Reference 11 describes the results of an FAA sponsored study of BCAS antenna diversity using the DOD Electromagnetic Compatibility Center's AIMS Performance Prediction Model and antenna patterns for a Cessna 150 aircraft obtained through model measurements by Lincoln Laboratory. The study provides plots of the direct path and multipath signal power levels that would be received by an omnidirectional BCAS antenna for various flight conditions and scattering surfaces. The ECAC report reaches the following conclusion (Reference 11, p. 11).

> "This analysis indicates that the diversity antenna system, as described in this report, offers multipath ratios and signal levels superior to single bottom mounted antennas. The improved performance occurs mainly at short range (separation <30 mi.) and in cases where the transmitting aircraft is above the victim receiver."

While each of these reports was generally helpful, they did not provide sufficient specific information. In particular, data contained in these various reports suffered from one or more of the following deficiencies with respect to the specific question considered by this report.

a. The aircraft used in previous tests were not of the small general aviation type.

b. The radio links evaluated were primarily between air and ground and not air-to-air as considered in this report.

c. The dynamic behavior of the BCAS software could not be easily predicted based upon the flight test or model data.

It was concluded that flight testing using the experimental BCAS system would be the most useful and efficient means of obtaining the required information.

2.2 SUMMARY OF TEST RESULTS

This section provides a summary of the test results. The observations made in this section are based upon data gathered during two days of testing using a single flight procedure (BCAS flying a 24-petal daisy pattern 2,500 feet above OTHER which was flying a figure eight). The results are based upon the operation of the experimental BCAS system installed in the FAA/NAFEC Grumman Gulfstream aircraft, N-48, and using the V-7 version of the BCAS software and higher gain ATCRBS antennas on the BCAS aircraft. The results obtained were derived through the use of an experimental system; therefore, the test observations may not be entirely representative of what may be achievable in future systems bases upon the BCAS concept. Observations concerning the data presented are true in a general sense; however, they may not hold in a small number of instances.

Table 2-1 lists calculated values of the maximum range at which the aircraft-to-aircraft cross-links could be expected to operate assuming 0 dBi antenna gain for all (BCAS and intruder) antennas. These calculated values are bases upon the transponder

power output and minimum trigger levels (MTL) listed in Table 2-2. A transmission line loss of 3.0 dB is assumed for the intruding aircraft. A 6.0 dB combined line, circulator, limiter, and filter loss is assumed for the BCAS receiver, and a 3.5 dB combined line and circulator loss is assumed for the BCAS interrogator. Table 2-1 indicates that, for the values chosen, the 1030 MHz interrogation link can be expected to set the range limit. Since the operating frequencies are very nearly the same and the paths identical, the antenna gains will be approximately the same for both links. Any increase or decrease from the assumed 0 dBi value will apply to both the 1030 and 1090 MHz links.

2.2.1 Dual Antenna Tests--Waterloo VORTAC

a) Tracking Interval (Active Mode)

The average aircraft separation distance at which tracking begins on the inbound leg (separation decreasing) and at which tracking ends on the outbound leg (separation increasing) is approximately 4.5 nmi for both top and bottom antennas. This value is near the tracking limit of 5.1 nmi for the top antenna. The limit is set by a BCAS range gate of 100 microseconds and the 37.5-microsecond delay intentionally introduced into the "top" transponder. Table 2-3 lists the aircraft separation distances at which tracking begins, R_i, and which tracking ends, R_f, for the dual antenna tests. The table shows that, for the top antenna, tracking begins and ends at either 4.8 or 4.9 nmi in 14 out of the 20 runs for which data are given (in Table 2-3). Thus, in most cases, the maximum range of target detection for the top antenna appeared to be limited by the conditions of the test and not the radio link margin. In the case of the bottom antenna, the situation is somewhat different. Here, the maximum range of detection is limited only by the 100-microsecond BCAS range gate which corresponse to 8.2 nmi. The maximum inbound and outbound range values (separation distances) shown in Table 2-3 are 7.6 and 6.3 nmi, respectively, for the bottom antenna. The corresponding average values are 4.3

TABLE 2-1. CLACULATED LIMITS OF A/C TO A/C CROSS LINKS

Antenna Location	R_{MAX} 1030-MHz Interrogation* Cross Link	R_{MAX} 1090-MHz Reply* Cross Link
C-172, Bottom	17.2 nmi	31.3 nmi
Bonanza, Top	29.6	75.2
Bonanza, Bottom	18.7	57.0

*Zero dBi aircraft antenna gains assumed.

TABLE 2-2. SUMMARY OF TRANSPONDER PARAMETERS

Transponder	Antenna Location	Power Out	MTL
RCA AVQ-63	Bonanza, Top	724 W*	-77 dBm*
BENDIX DABS	Bonanza, Bottom	416 W*	-73 dBm*
Cessna ART RT-359A	Cessna, Bottom	125 W, Typ.	-72 to -80 dBm**
BCAS (Dual Channel) 1090-MHz Receiver	BCAS, Top and Bottom	N/A	-86 dBm at circulator antenna port.
BCAS 1030-MHz Interrogator	Switched between BCAS Top and Bottom	500 W at antenna port on interrogator.	N/A

*Measured value
** Minus seventy-two dBm used for calculations.

TABLE 2-3. LIMITS OF TRACKING IN NAUTICAL MILES

RUN	BCAS, TOP ANTENNA				BCAS, BOTTOM ANTENNA			
	Inbound		Outbound		Inbound		Outbound	
	R_i	R_f	R_i	R_f	R_i	R_f	R_i	R_f
1	4.7			4.7			2.2	5.7
2	4.8			4.8			2.0	5.0
3							2.0	5.3
4					3.5	2.5	2.7	4.7
5	4.9			4.8			2.1	5.8
6	4.8			4.9	3.7	2.0	2.0	2.8
7	4.8			4.8	3.6			4.8
8	4.8			4.9	4.1	2.1		
9	4.8			4.8	5.1	2.7		
10	4.8			4.9	7.6	2.1	2.2	6.3
11	3.1			4.0	3.1	2.9	1.8	3.9
12	2.5			4.7	2.5	2.0	2.9	3.7
13	4.9			2.6	5.6	2.0		
14	3.7			1.1	3.7	2.0		
15	4.9			4.8	4.8	2.5	2.2	2.5
16	4.1			4.7				
17	4.9	3.0	0.7	4.9	4.5	2.9	1.7	4.7
18	Insufficient data				Insufficient data			
19	No data				No data			
20	4.9			4.8			1.7	4.5
21	4.9			4.8	4.1	2.0	1.8	6.0
22	4.9			4.8			1.8	3.0
23	4.9			4.8			1.8	5.9
24	4.6			4.9			2.0	6.3
Mean	4.54			4.48	4.30	2.31	2.06	4.76
Std. Dev.	0.67			0.95	1.29	0.37	0.34	1.22

and 4.8 nmi, respectively, both well below the 8.1 nmi system range gate limit. Consequently, tracking of the bottom antenna was apparently limited in all but perhaps one instance by the radio link margins.

b) Tracking Continuity (Active Mode)

The data in Table 2-3 show that tracking of the top antenna was, with the exception of Run 17, continuous throughout the cross-over region. Conversely, tracking of the bottom antenna was lost in all but one case in the vicinity of crossover. This result is not surprising inasmuch as the bottom antenna of the Bonanza (intruding aircraft) becomes more shielded from the higher-flying BCAS aircraft as they near the cross-over point. The interval over which tracking is lost in the case of the bottom antenna extends approximately 2 nmi on either side of crossover. The region seems to be surprisingly well defined with means and standard deviations of 2.31 and 0.37 nmi inbound, and 2.06 and 0.34 nmi outbound, respectively.

c) Garbled Replies (Active Mode)

Garbled replies received from the bottom antenna were generally confined to the vicinity of crossover and occurred on nearly every run. No garbled replies were received from the intruding aircraft's top antenna. A garbled reply occurs when the BCAS software is unable to decode properly the beacon code of the intruding aircraft's reply. In these tests, the garbled reply was associated with the intruding aircraft due to its known time relationship to the reply from the intruding aircraft's top antenna.

d) Multipath (Active Mode)

Target declarations due to multipath scattering shows in approximately half of the runs (i.e., runs 2,5,7,9,10,11,15,21, and 24). Relatively strong multipath scattering can be expected from the ocean surface and relatively weak scattering from rural terrain. Multipath data gathered by Lincoln Laboratory indicate that especially strong scattering can be expected from a smooth water surface.

The Coast Guard report indicates that smooth sea conditions (sea state 1 or less) existed in Delaware Bay on the test day. Of the 24 multipath replies received, 19 occur at points for which the scattering region is believed to have been over water. Three returns appear to have taken place at points for which the scattering surface was over land, and two are points for which the probable scattering region is too close to the shoreline to predict. Twenty-three of the multipath targets are associated with replies from the intruding aircraft's bottom antenna and only one with the top antenna. Thus, the multipath target declarations observed are quite consistent with expectations.

e) Estimated Antenna Gain, Bottom Antenna of Intruding Aircraft

The gain of the intruding aircraft's bottom antenna in the direction of the BCAS aircraft is plotted in Figures 5-22 and 5-23. With the exception of Run 16, the gain values are between -7 and +1 dBi on the inbound legs, and between +3 and +6 dBi on the outbound legs. Run 16 has gain values ranging from -5 to +7 dBi outbound. No pattern data were available for the points on the inbound leg of Run 16. The antenna gain values plotted in Figures 5-22 and 5-23 tend to support the tracking performance indicated in Table 2-3 and in the corresponding TOA plots.

2.2.2 Single Antenna Tests--Millville VORTAC

Active versus Passive Mode

Unlike the Dual Antenna Tests for which only active mode data are presented, the Single Antenna Tests involve data gathered in both modes of operation. In general, both active and passive modes of operation provide tracking throughout the same approximate regions of each run. Only occasionally, did one mode of operation provide coverage to compensate for poor performance of the other mode.

Even in the case of BCAS approaching the intruder from below (Run 25), antenna coverage appeared to be better to the rear of the intruding aircraft than in the forward part of its pattern.

2.2.3 Dual Antenna and Single Antenna Test Comparison

Tracking versus Heading Differences

When the headings of the BCAS and intruding aircraft differ by more than 90 degrees, BCAS performance was poorer before crossover than after. Conversely, when aircraft headings differed by less than 90 degrees, performance was generally better before crossover than after. This latter observation was somewhat more strongly evident in the single antenna (Cessna 172 intruder) than in the dual antenna tests (Bonanza intruder).

3. CONCLUSIONS AND RECOMMENDATIONS

An attempt to resolve the antenna diversity question for general aviation aircraft using available data was not successful. Two major deficiencies were noted in the relevant reports: (a) analysis did not consider the actual BCAS hardware capability and (b) flight situations/encounters for the conducted flight tests were not adequate for making definitive conclusions with regard to BCAS. New tests, although limited, were conducted to check some difficult but representative flight encounters either to answer and antenna diversity question or to recommend a more in-depth study in the future. Even on the basis of limited testing, it was consluded that a single bottom-mounted antenna may pose a problem. Antenna diversity may be required for the general aviation aircraft operating with BCAS in order to provide adequate protection in marginal situations; e.g., for an encountering aircraft flying below BCAS. This was shown to be true in head-on encounters for which tracking of the intruding aircraft equipped with only a bottom antenna is poor. This conclusion is supported by both the dual antenna using the Beechcraft Bonanza as the intruder and by the single antenna tests run with the Cessna 172. Figures 5-4 and 5-40 summarize the data supporting this conclusion.

It is therefore recommended that additional testing be conducted in order to determine the degree to which antenna diversity on small general aviation aircraft (OTHER) can be expected to improve BCAS performance. Additional test results should permit the determination of whether or not antenna diversity is a requirement for the general aircraft.

PART II: PERFORMANCE ESTIMATES AND MEASURED VALUES

4. SYSTEM PERFORMANCE ESTIMATES

Estimates were made of the expected performance of the BCAS system in order to highlight potential problem areas and to provide a framework against which flight tests could be specified and conducted. Estimates are made of link margins and signal-to-multipath ratios based upon measured antenna paterns (derived from scale models) and multipath scattering data(obtained by Lincoln Laboratory).

4.1 LINK CONSIDERATIONS

4.1.1 SSR-to-Aircraft Uplink

The uplink from the SSR radar to an intruding aircraft is considered first. The uplink to the BCAS aircraft is not considered since the BCAS airfcraft will have antenna diversity, and the BCAS system is assumed to be locked to the SSR in question (a necessary condition to obtain target information in the passive mode). Performance of the uplink from the SSR to the intruding aircraft will depend in part upon the effective isotropic radiated power (EIRP) of the SSR. ATCRBS system line-of-sight coverage is typically up to 200 nmi for enroute radars with reduced ranges used for terminal area radars. In all cases we assume that, for the purposes of this study, the uplink for all locked radars is adequate to maintain lock. The BCAS system can switch automatically to active interrogation to compensate for a partial or full loss of SSR interrogation of the intruding aircraft.

4.1.2 Aircraft-to-Aircraft Crosslinks

a) Reply Link 1090 MHz

Table 4-1 lists the pertinent parameters of the reply link used for the reception of replies from the intruding aircraft which are elicited by ground-based radars. The minimum value of power output from the ATCRBS transponder; i.e., 18.5 dBW at the antenna end of the transmission line, 0 dBi antenna gains, and a 3-dB RF transmission line loss in the BCAS system, is assumed. Using these

TABLE 4-1. BCAS AND ATCRBS SYSTEM PARAMETERS

1090 MHz Receiver (BCAS)	
Sensitivity:	-86 dBm signal at BCAS RF port P_D = 99% single pulse detection P_N = 10^{-6} thermal noise pulses
Dynamic Range:	70 dB log video
Bandwidth:	10 MHz
1030 MHz Receiver (BCAS)	
SLS Sensivity:	-90 dBm signal at BCAS RF Port. P_D = 99% single pulse detection P_N = 0.2% thermal noise pulses (10^{-3} prob. of false SLS decode in a 3 msec. gate)
Main Beam Sensitivity:	-65 dBm signal at BCAS RF port for P_D = 90%
Bandwidth:	3 MHz
ATCRBS Transponder	
Sensitivity:	Minimum triggering level, MTL, equal to -71 dBm nominal (-69 to -77 dBm) at antenna end of transmission line for 90% reply probability. A nominal line loss of 3 dB is assumed.
Random Triggering Rate:	Less than 30 replies per second when integrated over an interval equivalent to at least 300 random replies or 30 seconds whichever is less with all possible interfering equipments operating normally.
Power Output:	For aircraft operating below (above) 15,000 feet the peak pulse power available at the antenna end of the transmission line of the transponder shall be at least 18.5 dBW (21 dBW) and not more than 27 dBW. A nominal transmission loss of 3 dB is assumed.

values and the required 20-nmi operating range (path loss of 124.6 dB), the received signal power level is -76.1 dBm at the BCAS antenna output. Allowing 3.0 dB for transmission line loss, 0.5 dB for the circulator, 2.0 dB limiter loss, and 0.5 dB RF filter loss,[12] we have a signal level of -82.1 dBm into the BCAS RF amplifier whose noise figure is given as 3.0 dB.[13] An antenna noise temperature of 290°K gives a system noise temperature of 580°K referred to the RF amplifier input. The noise power within the 10-MHz BCAS passband is -101.0 dBm leading to an IF signal-to-noise ratio of 18.9 dB. Since a signal-to-noise ratio of 14.5 dB is required to provide a single-pulse detection probability (P_D) of 99 percent with a false-alarm probability of 10^{-6} (see Ref. 19, Figure 1.9), we have a net link margin of only 4.4 dB at a range of 20 nmi assuming 0-dB antenna gains, and no multipath fading.

b) Interrogation Link: 1030 MHz

The quality of the interrogation link from BCAS to OTHER is estimated by assuming a BCAS interrogator power output of 500 watts,[12] the circulator loss at 0.5 dB, and the line loss at 3.0 dB. The power level at the BCAS antenna is then 53.5 dBm. The path loss for 20 nmi is 124.1 dB. Assuming 0-dBi antenna gains gives a signal level of -70.6 dBm at the antenna end of the ATCRBS transponder transmission line. The ATCRBS specification as given in Table 4-1 is -71 dBm nominal (-77 to -69 dBm) for P_D of 90 percent. Therefore, a link margin is -1.6 dB for the worst case MTL of -69 dBm. Clearly, 20 nmi appears to be about the maximum range at which the active mode of BCAS can operate. Any signal loss due to antenna nulls would restrict the effective range of the system to less than 20 nmi.

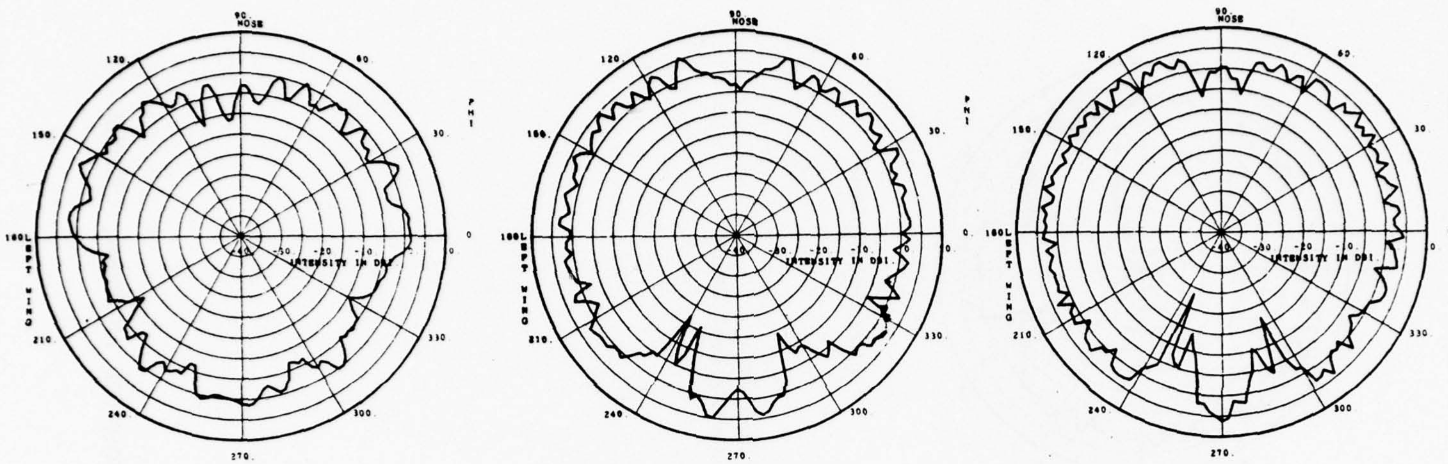
4.1.3 Aircraft Antenna Gain

Zero-dBi antenna gains for both BCAS and OTHER have been considered so far; however, the actual antenna gain acheived will depend upon a number of factors including the aircraft type and configuration, antenna location, and the orientation of the aircraft with respect to the radio path between the aircraft. The following

examples serve to highlight certain antenna considerations. Antenna patterns obtained by Lincoln Laboratory[14] through the use of 1/20-scale models are shown in Figure 4-1 and are used for illustration. The antenna pattern in the horizontal plane varies with the fore-and-aft location of the antenna. The plots shown are for a Gates Lear Jet (model) with landing gear and flaps extended. Nulls are produced at approximately ±30 degrees of the tail of the aircraft as the antenna is moved forward to the center and front locations. Figure 4-2 illustrates the effect of aircraft configuration on the antenna pattern. The effect produced by landing gear and flap extension is particularly noticeable at ±30 degrees of the tail where nulls of approximately 15-dB depth are evident. More shallow nulls can be seen at the nose and tail. Figure 4-3 illustrates the sensitivity of antenna pattern to aircraft type. The patterns shown are for the bottom-mounted center location on the Lear Jet and the Beech B-99 using 1/20-scale model data. The deepest nulls occur at ±30 degrees of the tail in the case of the Lear Jet, while the Beech B-99 pattern has its deepest nulls just aft of the right-and left-wing positions. These figures serve simply to illustrate the sensitivity of aircraft antenna patterns to the location of the antenna on the aircraft (Figure 4-1), aircraft configuration (Figure 4-2), and aircraft type (Figure 4-3).

4.1.4 Multipath

The second point for consideration is the relative antenna gain provided to the direct path from BCAS to the intruding aircraft, OTHER, and to the indirect path from BCAS to OTHER via scattering/reflection from the earth's surface. Signal transmissions from OTHER to BCAS will arrive first via the direct path followed in time by "multipath" signals scattered from the earth's surface. Consider two co-altitude aircraft with horizontal separation. When the aircraft separation is relatively large and the altitudes are small compared with the separation, the angles of arrival of the direct-path signal and the multipath signal are approximately the same. The multipath signal arrives at a shallow angle below the local horizontal plane. In the absence of sharp nulls in this



horizontal plane

rear

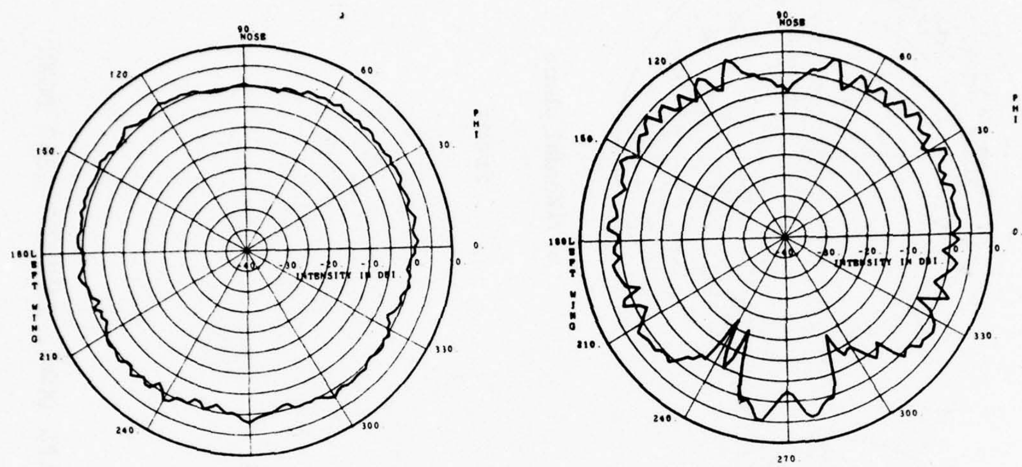
horizontal plane

center

horizontal plane

front

FIGURE 4-1. LEAR JET, BOTTOM MOUNTED ANTENNA, FLAPS DOWN, LANDING GEAR DOWN



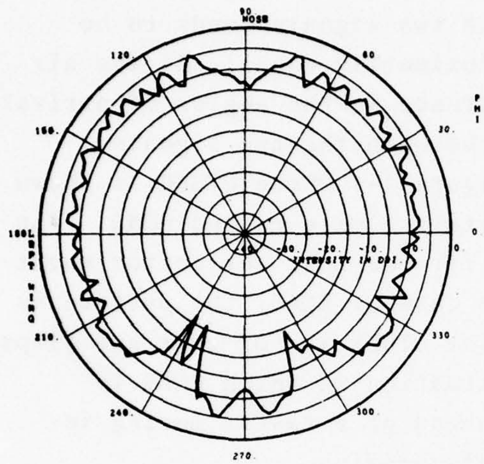
horizontal plane

Flaps up
Landing gear up

horizontal plane

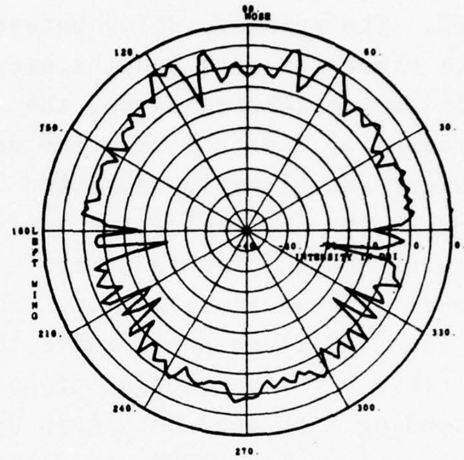
Flaps down
Landing gear down

FIGURE 4-2. LEAR JET, BOTTOM MOUNTED ANTENNA, CENTER ANTENNA LOCATION



horizontal plane

Lear Jet



horizontal plane

Beech B-99

FIGURE 4-3. HORIZONTAL PLANE ANTENNA PATTERNS, BOTTOM MOUNTED, CENTER LOCATION, FLAPS DOWN, LANDING GEAR DOWN

region, the BCAS antenna can be expected to provide approximately equal gain to both signals.

A similar situation exists at the transmitting antenna at OTHER. The relative delay between the two signals tends to be small since the path lengths are approximately equal. As the aircraft separation decreases, the difference in the angles of arrival increases as does the relative delay between the two signals. Consider the situation depicted in Figure 4-4 where OTHER is shown flying 1,000 feet below the approximately 1 mile behind BCAS. The patterns shown for both aircraft are for the Lear Jet bottom-mounted rear antenna installation. In the case of BCAS, the pattern is for gear and flaps down, while that for OTHER is for gear and flaps up. This might be thought of as a situation in which BCAS is descending with gear and flaps down ahead of a faster moving intruding aircraft, OTHER, in clean configuration.

Although the BCAS antenna provides approximately equal (within 2 dB) gain to both the direct and indirect paths, the pattern of OTHER provides approximately 14-dB less gain to the direct path than to the indirect path. As a consequence, the "multipath" signal enjoys an approximately 12-dB antenna gain advantage over the "direct-path" signal. Further, were the direct path to fall within rather than on the shoulder of the null in OTHER's pattern, it could suffer an additional 15-dB less gain. While the situation was chosen to illustrate a point, it is perhaps not totally artificial. Let us carry our example just one step further and consider the multipath scattering that might be expected. Using data obtained by Lincoln Laboratory[15] (and shown in Figure 4-5), we find that for scattering from the ocean (sea state 1) with both aircraft at 4,500-foot altitude, the signal-to-multipath ratio for a bottom-to-bottom link is approximately 0 dB. While the Lincoln Laboratory data include antenna effects, it is doubtful that antenna discrimination accounts for more than 5 to 10 dB. The path length difference between the indirect and the direct path is approximately 1,800 feet which corresponds to a multipath delay of 1.8 microseconds. A 1.8-microsecond delay would place the F_1 framing pulse

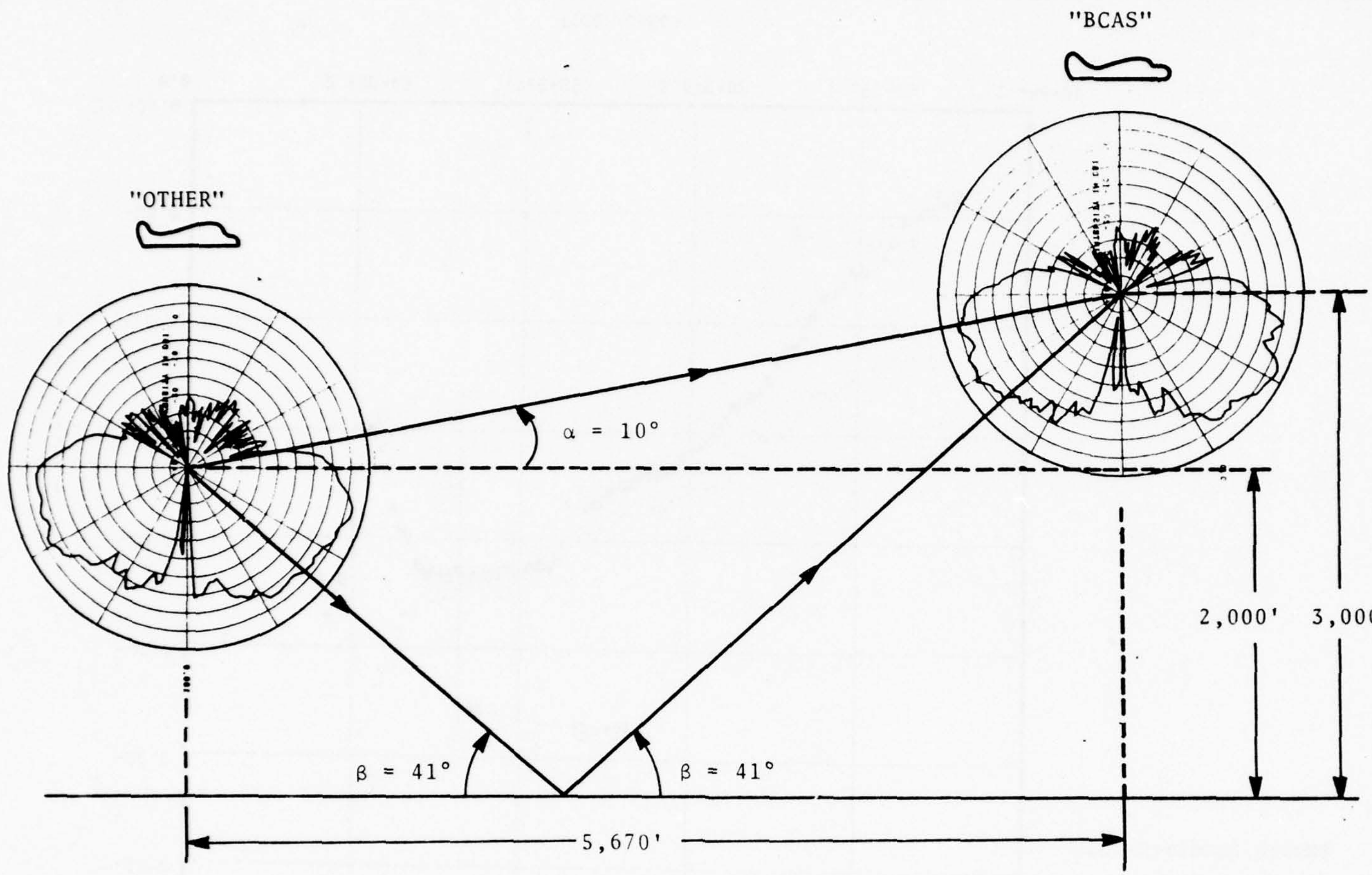


FIGURE 4-4. ILLUSTRATION OF MULTIPATH SCATTERING

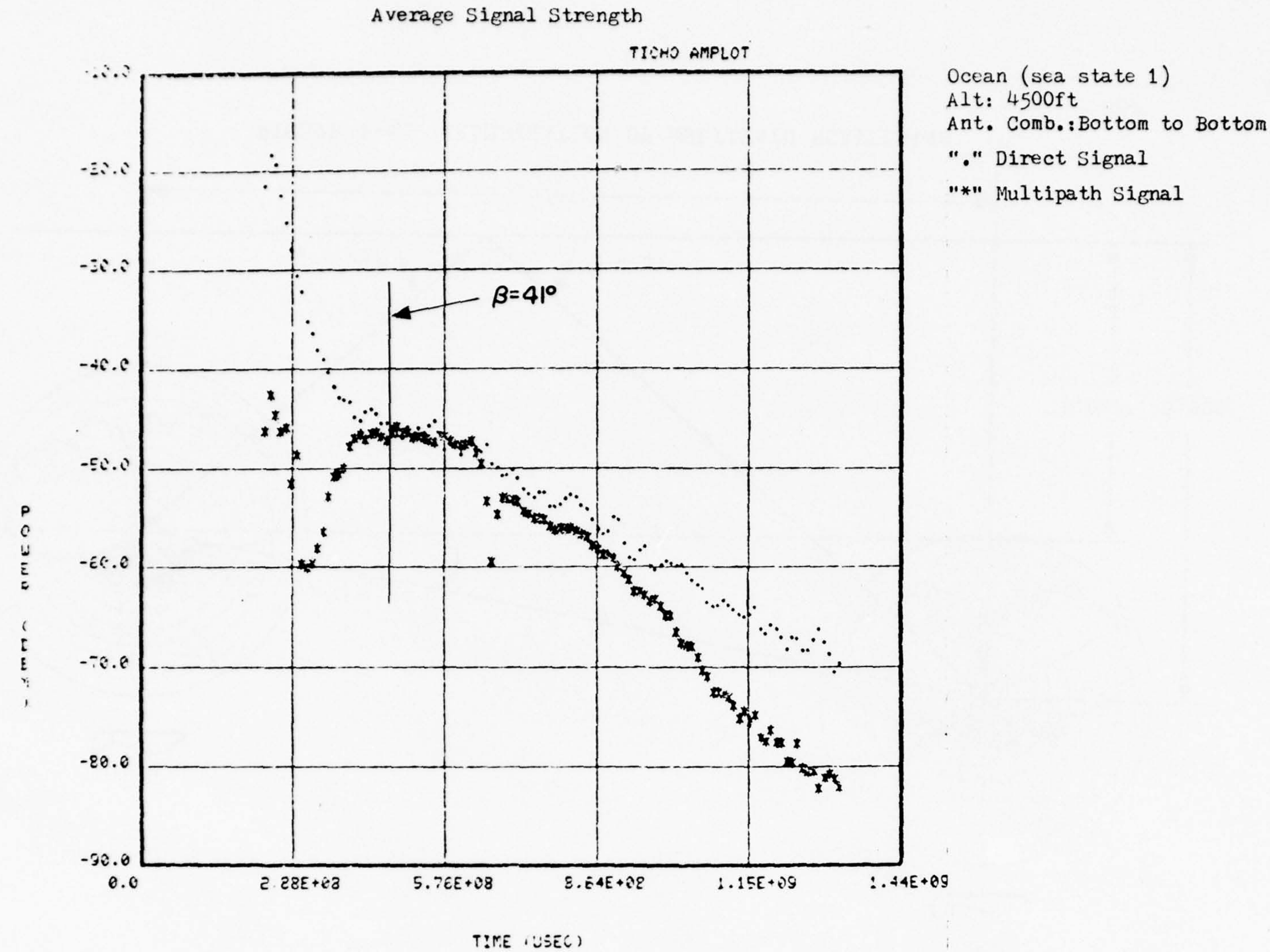


FIGURE 4-5. AVERAGE SIGNAL STRENGTH FOR DIRECT AND INDIRECT SIGNALS. (Courtesy: Lincoln Laboratory. Flight data taken from Reference 15, Figure 2.A.1)

of the multipath signal on the trailing edge of the C_1 pulse of the direct-path signal, the C_1 multipath pulse on the trailing edge of the direct-path A_1 pulse, etc. See reference 20 for a description of the ATCRBS reply transmission characteristics.

4.1.5 Statistical Distribution of Antenna Gains

Thus far, discussion of aircraft antenna patterns has been qualitative. At this point, we wish to make some estimates as to what antenna-gain margins might reasonably be required for reliable link operation. To accomplish this, we shall select two aircraft as being somewhat representative of the small general aviation population. The Cessna 150 is a high-wing fixed-landing gear single-engine aircraft, while the Piper Cherokee Arrow is a low-wing single-engine aircraft having retractable landing gear. We shall use the Lincoln Laboratory antenna data[16] for these aircraft to estimate the required link margins. Table 4-2 shows the 99 percent gain values for the Piper and Cessna aircraft for various flight conditions and bottom-mounted antenna locations. The 99 percent gain value is that value of antenna gain which is equaled or exceeded in 99 percent of the flight geometries under consideration. A more complete explanation of its meaning is given in Reference 16. Table 4-2 indicates that for level flight with gear and flaps up, the range of 99 percent gain vlaues is from -4.0 to -12.5 dBi for both aircraft and all antenna locations. If we include shallow and moderate roll and moderate pitch maneuvers (gear and flaps up), our range of 99 percent gain values goes from -4.0 to -22.3 dBi. However, if we exclude the -22.3 dBi (No. 3 antenna location on the Cherokee), we find the range is limited to -4.0 to -15.6 dBi. Using -4.0 to -15.6 dBi as the range of 99 percent gain values, we find the corresponding ranges for 0-dB link margins to be 20.9 and 5.5 nmi, respectively, for the 1090-MHz reply link. This corresponds to a 99 percent single-pulse detection probability with a false alarm probability of 10^{-6}. Similarly, for the 1030-MHz interogation link using a BCAS interrogater power output of 500 watts and a worst-case transponder (MTL of -69 dBM for P_D of 90 percent), we have link margins of -5.6 and -17.2 dB corresponding

TABLE 4-2. NINETY-NINE-PERCENT GAIN VALUES (dBi) FOR VARIOUS AIRCRAFT FLIGHT CONDITIONS AND BOTTOM-MOUNTED ANTENNA LOCATIONS (COURTESY: LINCOLN LABORATORY. VALUES TAKEN FROM DATA CONTAINED IN REFERENCE 16)

Aircraft	Piper Cherokee		Cessna 150		
Flight Condition \ Antenna Location	3	4	2	3	4
Level Flight, Gear and Flaps Up	-4.0	-10.6	-12.5	-6.2	-8.9
Shallow Roll, Gear and Flaps Up	-9.5	-11.4	-8.8	-4.9	-9.8
Moderate Roll, Gear and Flaps Up	-22.3	-15.6	-13.4	-10.8	-15.3
Moderate Pitch, Gear and Flaps Up	-9.2	-11.2	-12.6	-7.7	-10.9
Level Flight, Gear Down, Flaps Up	-10.3	-16.1	-12.2	-6.0	-8.9

NOTE: Level Flight, ± 3-degrees roll and/or pitch

Shallow Roll ± 15 degrees roll

Moderate Roll -30 degrees to -15 degrees and +15 degrees to +30 degrees roll

Moderate Pitch ± 15 degrees pitch

to the 99 percent gain values of -4.0 and -15.6 dBi, respectively. The corresponding ranges which provide 0-dB link margins at 1030 MHz are 10.5 and 2.8 nmi, respectively. Thus for the conditions assumed, the effective range of the 1030-MHz link is approximately one-half of that for the 1090-Mhz link.

5. MEASURED PERFORMANCE

The calculations referred to in Section 4 serve only as a guide to what might be expected in practice. A more realistic estimate of the possible need for antenna diversity in a BCAS was obtained by conducting two flight tests using the BCAS. The BCAS was installed in a Grumman Gulfstream aircraft and served as a threshold device to determine the adequacy of the various radio links. Target declaration by the BCAS software was used as the measure of system performance. When operating in the active mode, the BCAS system transmits a burst of 24 interrogations every 2.5 seconds. Twelve interrogations are transmitted via the bottom BCAS antenna, and twelve interrogations via the top BCAS antenna during each burst. Replies are received simultaneously via two separate receiver channels ("top" and "bottom"), and antenna selection for the received signal is bases upon time of arrival and a comparison of the video output voltages from the two channels. Target declaration for a given burst is made following the reception of at least six suitable replies during the given burst period. Similarly, in the passive mode the reception of six or more suitable replies from an intruding aircraft responding to an SSR radar during any one scan period also constitutes a target. The declaration of a valid target for any given scan is interpreted to mean that both the 1030-MHz interrogation link and the 1090-MHz reply link were adequate during that scan. The lack of a valid target declaration for any scan is interpreted to mean that one or both of the links were inadequate during that scan (i.e., replies were either not present or were garbled thereby preventing target declaration by the BCAS software). Certain garbled replies identified by post-flight computer processing of the data tapes are, however, discussed in Section 5.2.1.

5.1 TEST DESCRIPTION

This section describes the flight test which were conducted by FAA/NAFEC on 8 August and 29 September. The August tests employed a Beechcraft Bonanza equipped with dual antennas and trans-

ponders as the intruding aircraft. The tests were flown in the vicinity of the Waterloo VORTAC. This region is shown in Figure 5-1. The Waterloo VORTAC is located near the coast, placing much of the multipath scattering region over the Delaware Bay from which relatively strong multipath scattering could be expected. Additionally, much of the region is marshland which should also tend to enhance multipath scattering. The September tests were flown in the vicinity of the Millville VORTAC using a Cessna 172 as the intruding aircraft. The Cessna 172 was equipped with a single transponder and bottom-mounted antenna. The Millville region is generally rural and tree-covered and should provide only weak multipath scattering. While the Waterloo and Millville tests were similar in that the same patterns were flown (a 24 petal daisy over a figure eight), the scattering surfaces and the intruding aircraft were significantly different. The Beechcraft Bonanza is an example of a low-wing general aviation aircraft having retractable landing gear, while the Cessna 172 is a high-wing aircraft of fixed gear design.

5.1.1 Dual Antenna Tests, Waterloo VORTAC

The test consisted of flying the BCAS in a Grumman Gulfstream in a 24-petal daisy pattern over a small general aviation aircraft (OTHER) which was flying a figure eight. These patterns are shown in Figure 5-2. The aircraft headings for each run are shown in Table 5-1. Altitude spearation was 2,500 feet with the BCAS aircraft at 9,500 feet and the "OTHER" aircraft (a Beechcraft Bonanza) at 7,000 feet using the Waterloo VORTAC as a crossover point. The Beechcraft Bonanza was equipped with a Bendix DABS transponder which was operated in the ATCRBS mode. Transponder sensitivity was measured at -73 dBm for 95 percent reply probability and power output at 416 watts. Cable loss was estimated to be approximately 1.5 dB. The Bendix transponder was connected to the bottom-mounted ATCRBS antenna, the location of which is shown in Figure 5-3. A second transponder (an RCA Model AVQ-63) was installed in the Bonanza and connected to the "DABS-Top Transponder" antenna also identified in Figure 5-3. The RCA transponder was modified at NAFEC to

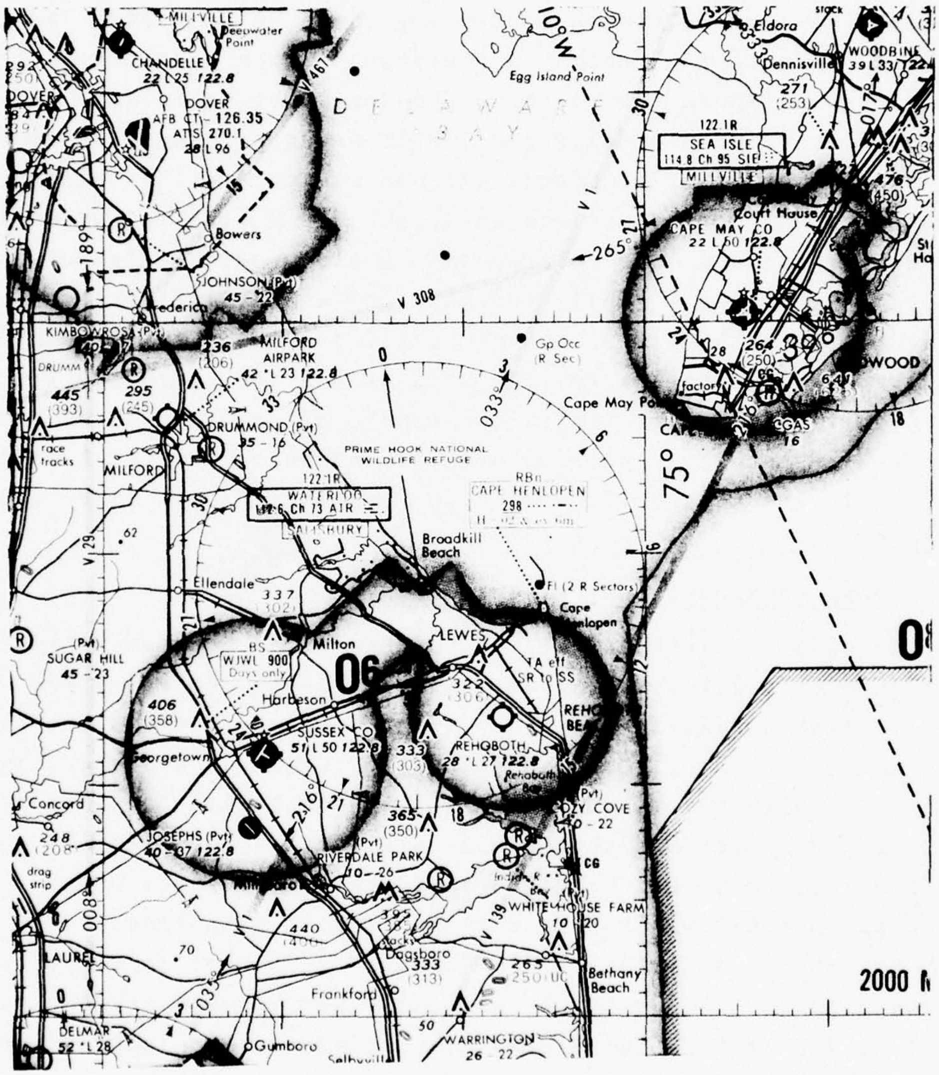


FIGURE 5-1. REGION SURROUNDING WATERLOO VORTAC

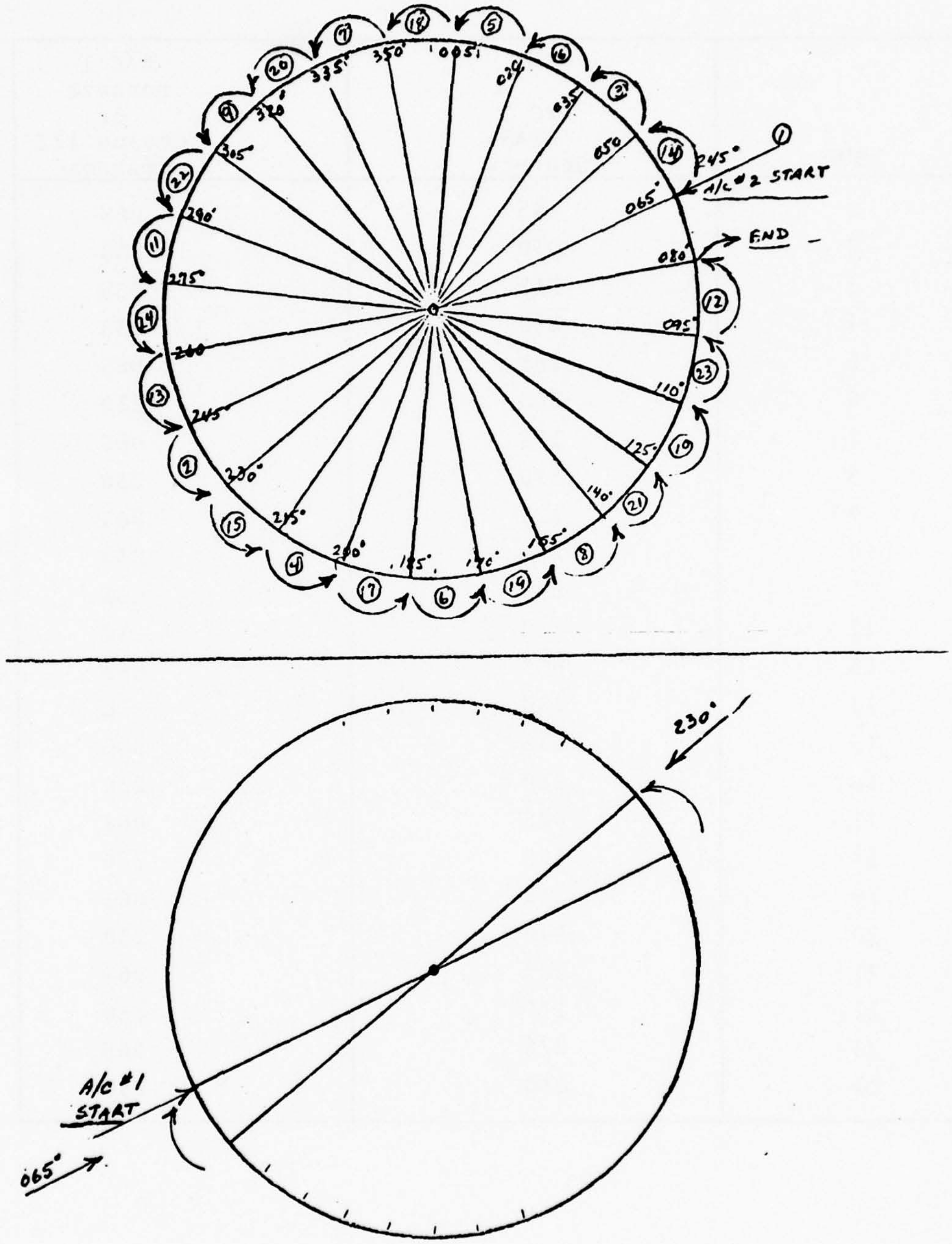


FIGURE 5-2. DAISY AND FIGURE EIGHT PATTERNS

TABLE 5-1. AIRCRAFT HEADINGS FOR DAISY PATTERN

RUN	A/C 2 (BCAS) degrees	A/C 1 Bonanza or Cessna 172 degrees
1	245	065
2	050	230
3	215	065
4	020	230
5	185	065
6	350	230
7	155	065
8	320	230
9	125	065
10	290	230
11	095	065
12	260	230
13	065	065
14	230	230
15	035	065
16	200	230
17	005	065
18	170	230
19	335	065
20	140	230
21	305	065
22	110	230
23	275	065
24	080	230

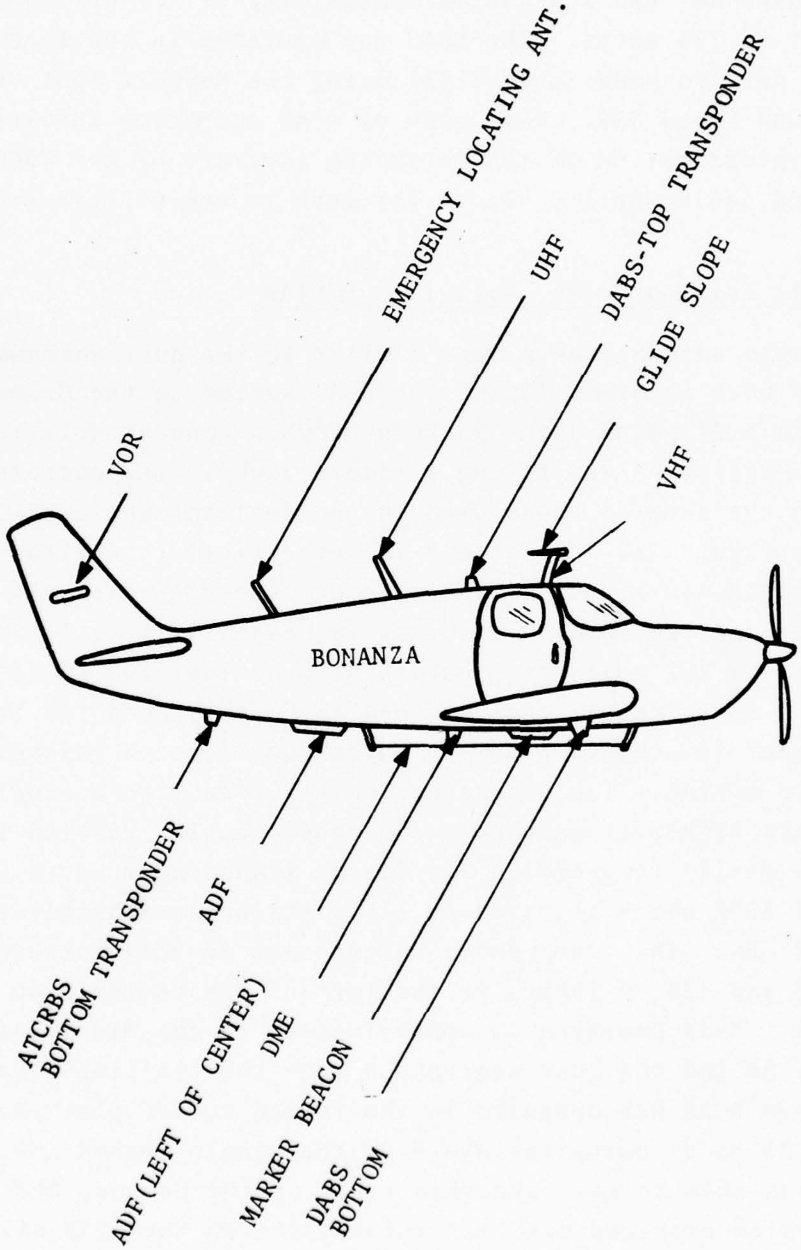


FIGURE 5-3. ANTENNA LOCATIONS, BONANZA --AUGUST 1977
(Courtesy: Lincoln Laboratory)

provide a 37.5-μs delay in its reply with respect to the "bottom" transponder. This delay prevented garbling of the two replies. The RCA transponder had a measured sensitivity of -77 dBm and a power output of 724 watts. The BCAS was operated in the forced active plus passive mode (mode I-33) using the Newport Test Van for the ground-based SSR. This mode of BCAS operation involves continuous interrogation of the intruding aircraft by the "BCAS" aircraft, and additionally, allows for lock to one or more ground-based SSR.

5.1.2 Single Antenna Tests, Millville VORTAC

The single antenna tests were similar to the dual antenna tests in that they both involved flying the BCAS system in the Grumman Gulfstream in a 24-petal daisy pattern above a general aviation aircraft (OTHER) which was flying a figure eight. The patterns and headings are the same as those used in the dual antenna tests, and are given in Figure 5-2 and Table 5-1, respectively. Altitude separation was maintained at 2,500 feet although the BCAS aircraft flew at 5,500 feet and the "OTHER" aircraft (a Cessna 172) at 3,000 feet. Since the Cessna 172 could only curise at a nominal 105 knots (150 knots for the Gulfstream), the legs had to be shortened for the Cessna in order to achieve nearly simultaneous station passage over the Millville VORTAC. The Cessna was only fitted with a single bottom-mounted ATCRBS transponder, and consequently, garbled replies could not be easily recovered. The Cessna transponder was a Cessna Model ARC-RT 359A which is rated at 125 watts and a sensitivity of at least -72 dBM. The transponder antenna was mounted between stations 123 and 125, 6 inches to the left of the center line of the aircraft. This position is approximately in the middle of the baggage area behind the rear seat and aft of the trailing edge of the wing. The BCAS was operated in the forced active plus passive mode (the I-33 mode) using the ASR-5 as the single locked SSR. The EAIR radar was able to maintain skin track on the Cessna, and the TACAN/DME system provided position information on the BCAS aircraft. As mentioned previously, only weak multipath scattering was anticipated in the single antenna tests at Millville.

5.2 TEST RESULTS

5.2.1 Dual Antenna Tests, Waterloo VORTAC

Figure 5-4 shows the time intervals over which target declarations were made for both the top- and bottom-mounted transponders for each of the 24 encounters of the daisy pattern. The relative bearing of the intruding aircraft with respect to the heading of the BCAS aircraft is indicated by the angle Ø, with 0 degrees taken as directly ahead and positive values increasing in a CW direction toward the right wing. The data represented by the entries in Figure 5-4 are exclusively associated with replies elicited by BCAS (active mode), and do not involve the Newport Test Van. Reception of replies elicited by the test van occurred so infrequently that the data were not considered useful. While the figure shows only the presence or absence of target data and does not indicate data quality, it does exhibit certain interesting features. Since the relative bearing, Ø, of the intruding aircraft as seen from the BCAS aircraft remains the same for run pairs (i.e., Runs 1 and 2, 3 and 4, etc.) with only the orientation with respect to the ground changing for each run, we might expect the system operation in the active mode to remain essentially unchanged for run pairs. Note however, that the scattering region for multipath changes as the aircraft are on opposite sides of the VORTAC on successive runs. Consequently, we can expect to see a certain repeatability in the data for run pairs with possible differences due to multipath scattering and the inherent non-repeatability of the experiment (e.g., wind effects, antenna pattern asymmetry, etc.). Examination of Figure 5-4 shows very little correlation between run pairs although there is a rather significant change as one progresses through the runs. Note the Runs 1 and 2 which involve head-on encounters show a relatively short time span (approximately one minute before and after crossover) during which a target was identified for the top transponder. Additionally, note that no target was declared for the bottom transponder until after crossover. As a contrast, consider Runs 13 and 14 which correspond to the tail-chase situation, where BCAS appears to have overtaken OTHER during the run. These runs show target declaration over a relatively long

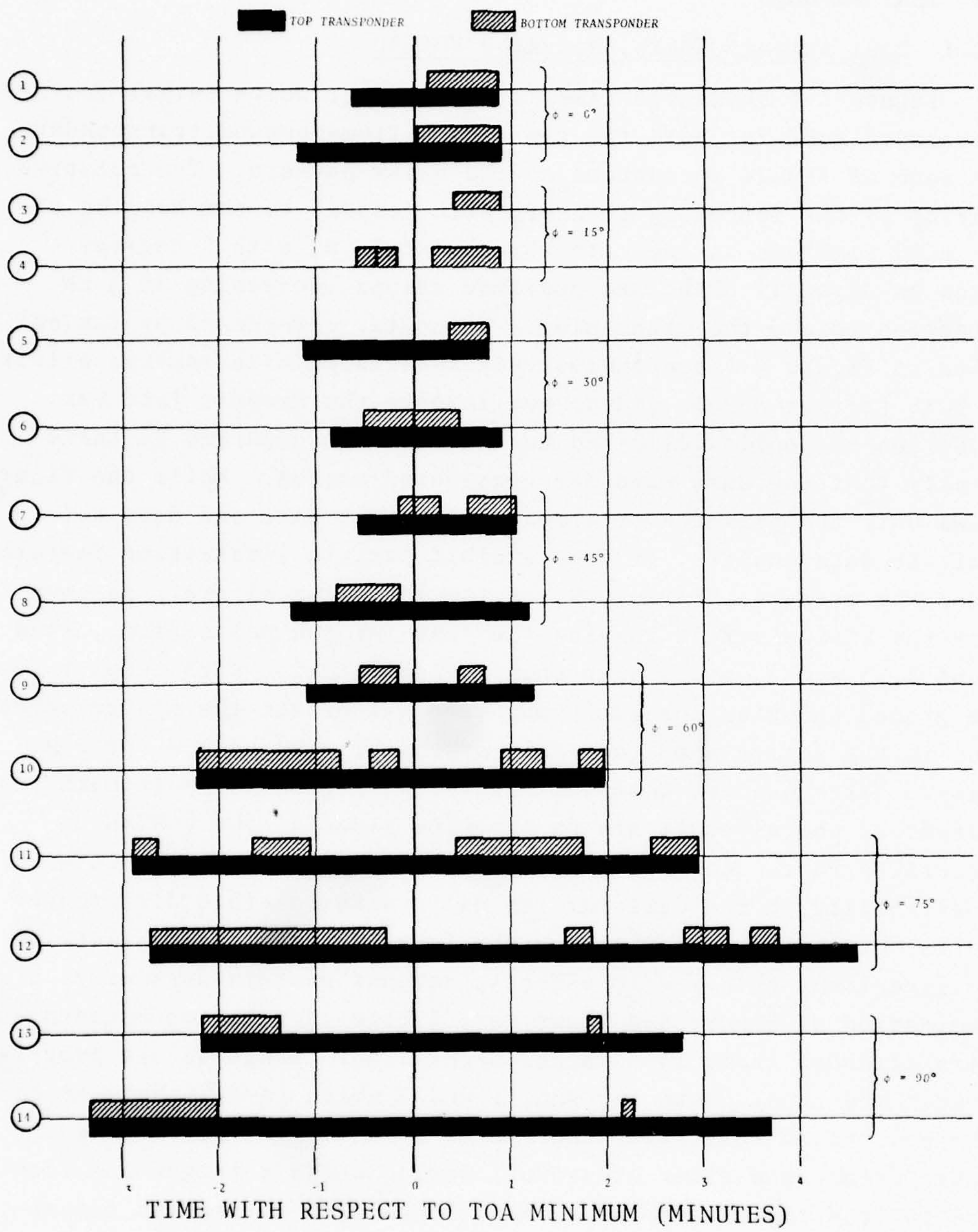


FIGURE 5-4. REGIONS OF TARGET DECLARATION - DUAL ANTENNA TESTS, WATERLOO VORTAC, ACTIVE MODE

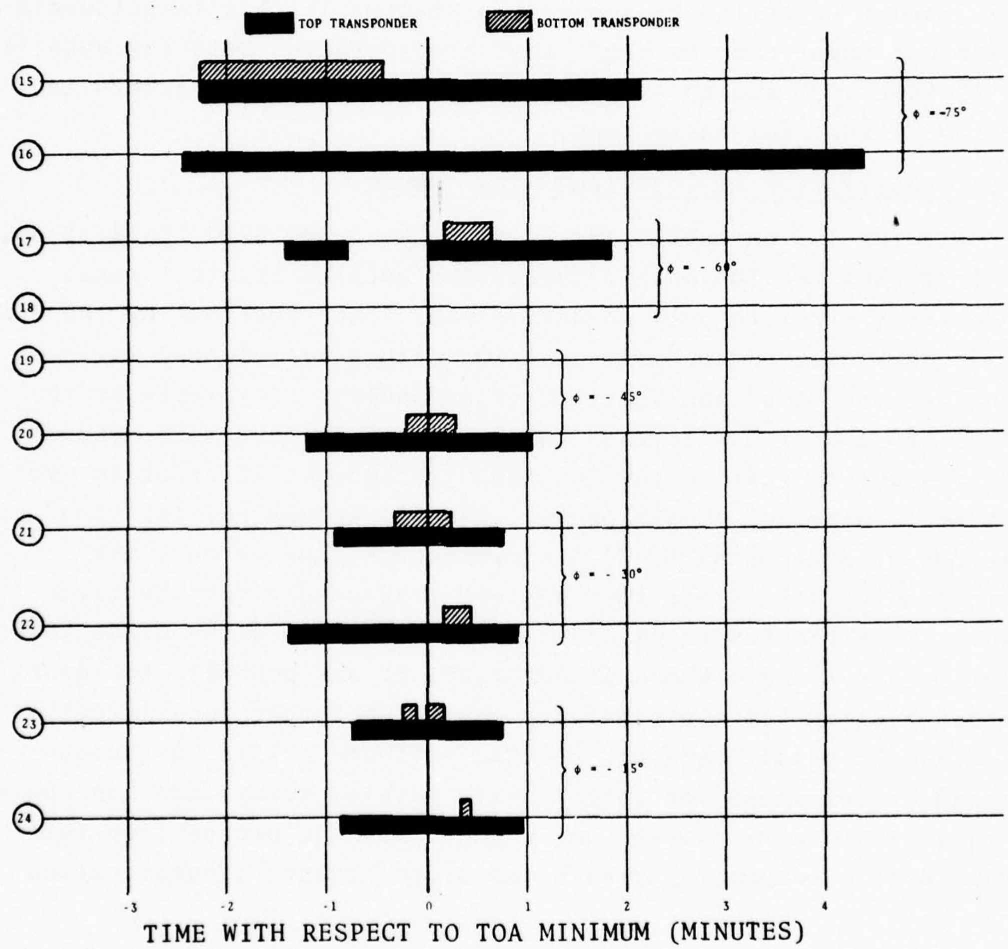


FIGURE 5-4. REGIONS OF TARGET DECLARATION - DUAL ANTENNA TESTS, WATERLOO VORTAC (CONTINUED)

period of time with the bottom transponder tracked during the early part of the run and then lost but for a brief period occurring approximately two minutes after crossover. Runs wherein the intruding aircraft is viewed more nearly from the side by the BCAS aircraft (i.e., Ø = ±15 degress, ±30 degrees, ±45 degrees, ±60 degrees, and ±75 degrees) generally show tracking of the "bottom" transponder both before and after crossover although tracking is not continuous as is generally the case for the "top" transponder. Runs 3 and 4 appear to be somewhat anomalous in that target declaration was never made for the "top" transponder. Data for Runs 18 and 19 were lost due to the presence of "illegal" characters in the tape format for these runs.

5.2.2 Description of Individual Test Runs

Figures 5-5 through 5-19, 5-26, 5-28, 5-30, 5-32, 5-34, 5-36, and 5-38 show the TOA data obtained for each of the test runs. These figures relate only to active mode interrogations by the BCAS, and do not involve the test van. TOA values are plotted for each scan for both "top" and "bottom" transponders. The reply of the "top" transponder was intentionally delayed by 37.5 microseconds with respect to that of the "bottom" transponder in order to prevent reply overlap. Consequently, the TOA values for the "top" transponder are nominally 37.5 microseconds greater than the corresponding values for the "bottom" transponder for any given scan. Since the two transponders were operating with unique identification codes and a known fixed delay, it was possible to identify garbled replies for those targets for which target identification could not be established by the BCAS software. This was accomplished by searching for targets with garbled identification codes falling within a ±3-microsecond window with the proper time relationship to a target reply with the proper beacon identification code.

Additionally, the occurrence within a single scan of two targets with the same beacon identification code was plotted as two distinct TOA values, indicating the presence of a possible false-target declaration due to surface multipath scattering. TOA data

are plotted with respect to time with the time axis labeled in units of seconds with respect to the time of closest passage of the BCAS and target aircraft as determined by the passage of the TOA through its minimum value. When the system is operating in the active interrogation mode, the TOA value is simply the signal round-trip time between two aircraft. This is true only for the "bottom" (undelayed) transponder. In those cases for which no TOA minimum (i.e., point of zero slope) exists, an extrapolated TOA minimum time was used where possible. Monotonically increasing or decreasing TOA were plotted with their initial or final values arbitrarily centered on the zero-time reference. The following points may prove helpful when interpreting Figures 5-5 through 5-19, 5-26, 5-28, 5-30, 5-32, 5-34, 5-36, and 5-38.

a) The vertical (TOA) scale is labeled from 0 to 100 microseconds. The 100-microsecond limitation on TOA values is imposed by the BCAS software which simply does not process data for which the TOA value exceeds 100 microseconds. The consistency of much of the data from the top transponder would lead one to expect that adequate tracking might have been possible at ranges corresponding to TOA significantly in excess of the 100-microsecond limitation. Since the "top" transponder suffers a 37.5-microsecond internal delay, a TOA value of 100 microseconds corresponds to a range of only 5.06 rather than 8.10 nmi as is the case for the "bottom" transponder. As stated previously, the sensitivities and power outputs of the "top" and "bottom" transponders were measured at -77 dBm and 724 watts, and -73 dBm and 416 watts, respectively. Thus, the "top" transponder had an approximate 3-dB advantage in both sensitivity and output power capability over the "bottom" transponder.

b) TOA data have been plotted with respect to time relative to aircraft crossover. This is consistant with the notion of the TAU logic used in BCAS wherein range divided by range rate is compared with a threshold value to determine the alarm condition. In the presentation given in Figures 5-5 thorugh 5-19, 5-26, 5-28, 5-30, 5-32, 5-34, 5-36, and 5-38, the most significant parameter is

the presence or absence of a target. The actual TOA value associated with a given target declaration serves mainly as a convenient parameter for graphic display. Additionally, plotting the TOA values provides a convenient means of displaying the presence of a multipath target.

5.2.2.1 Runs 1 to 15 (Figures 5-5 through 5-19)

Aircraft position data are not available for the Beechcraft Bonanza for Runs 1 to 15. Since both aircraft were equipped with VOR/DME, it is assumed that they were maintaining reasonably good tracks during the test runs. No attempt has been made, however, to determine relative viewing angles from one aircraft to the other; nor has an attempt been made to compute multipath scattering angles or path delays corresponding to selected data points for these runs. The Beechcraft Bonanza was not equipped to be tracked by the EAIR radar when operating in the vicinity of the Waterloo VORTAC. The EAIR radar did track the much larger "BCAS" aircraft as shown in Figure 5-20. Figures 5-5 and 5-6 correspond on head-on approaches (ϕ of 0 degree). The "top" transponder was tracked with little difficulty within the BCAS range gate; i.e., TOA $\leq$ 100 microseconds, while the "bottom" transponder was tracked only after aircraft crossover. Replies from the "top" transponder were decoded unambiguously with only one target declaration missing.

Replies from the "bottom" transponder were garbled as indicated by the asterisk rather than the plus in the vicinity of crossover. Additionally, there were a few more missed targets associated with the "bottom" transponder. Evidence of a single multipath reply associated with the "bottom" transponder can be seen in Figure 5-6. Figures 5-7 and 5-8, ϕ of 15 degree, correspond to nearly head-on encounters for which the intended ground tracks (VOR radials) intersect at 30 degree. These plots are unique in that they show no TOA values for the "top" transponder. No explanation was found for the lack of target declarations for these runs.

Since "top" transponder replies were not available during Runs 3 and 4, it was not possible for the computer data reduction program to identify possible garbled replies. Examination of the tar-

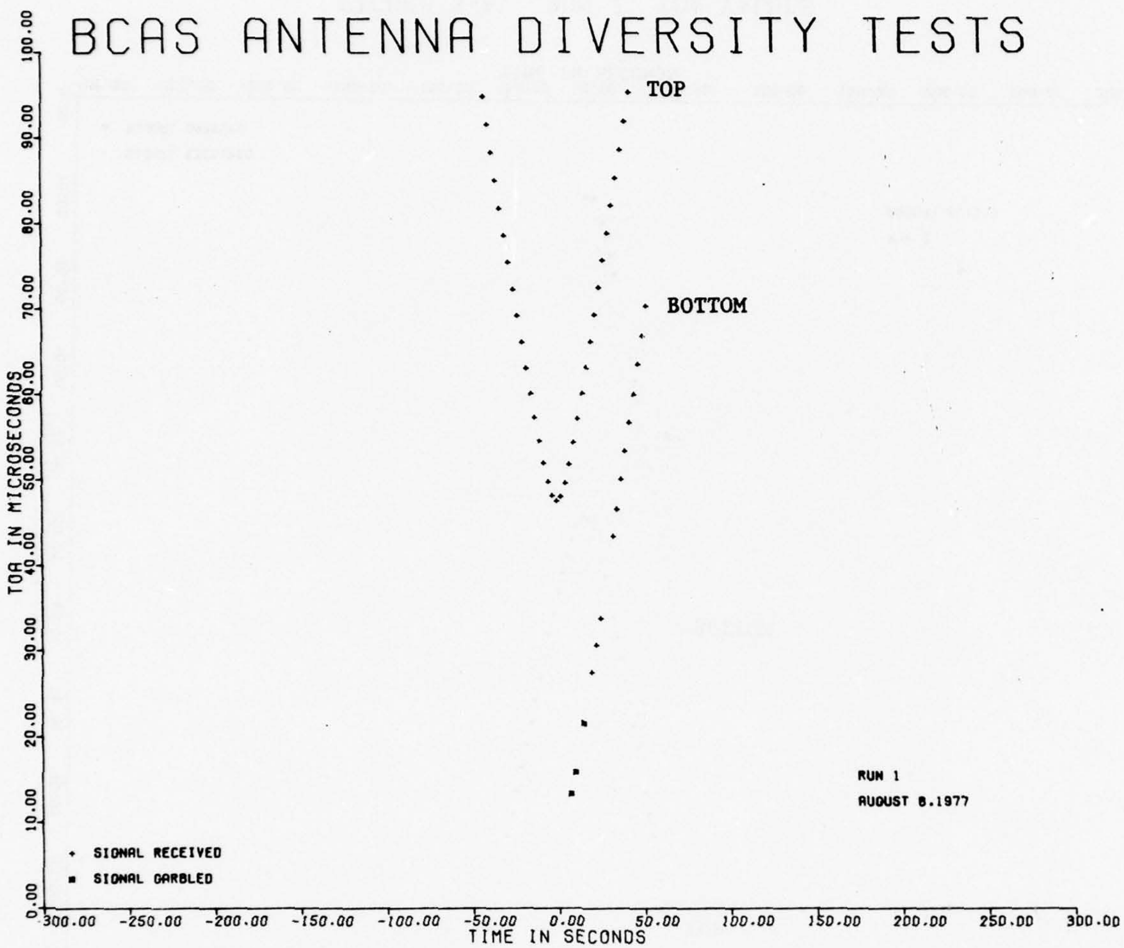


FIGURE 5-5. RUN 1, TOA VALUES

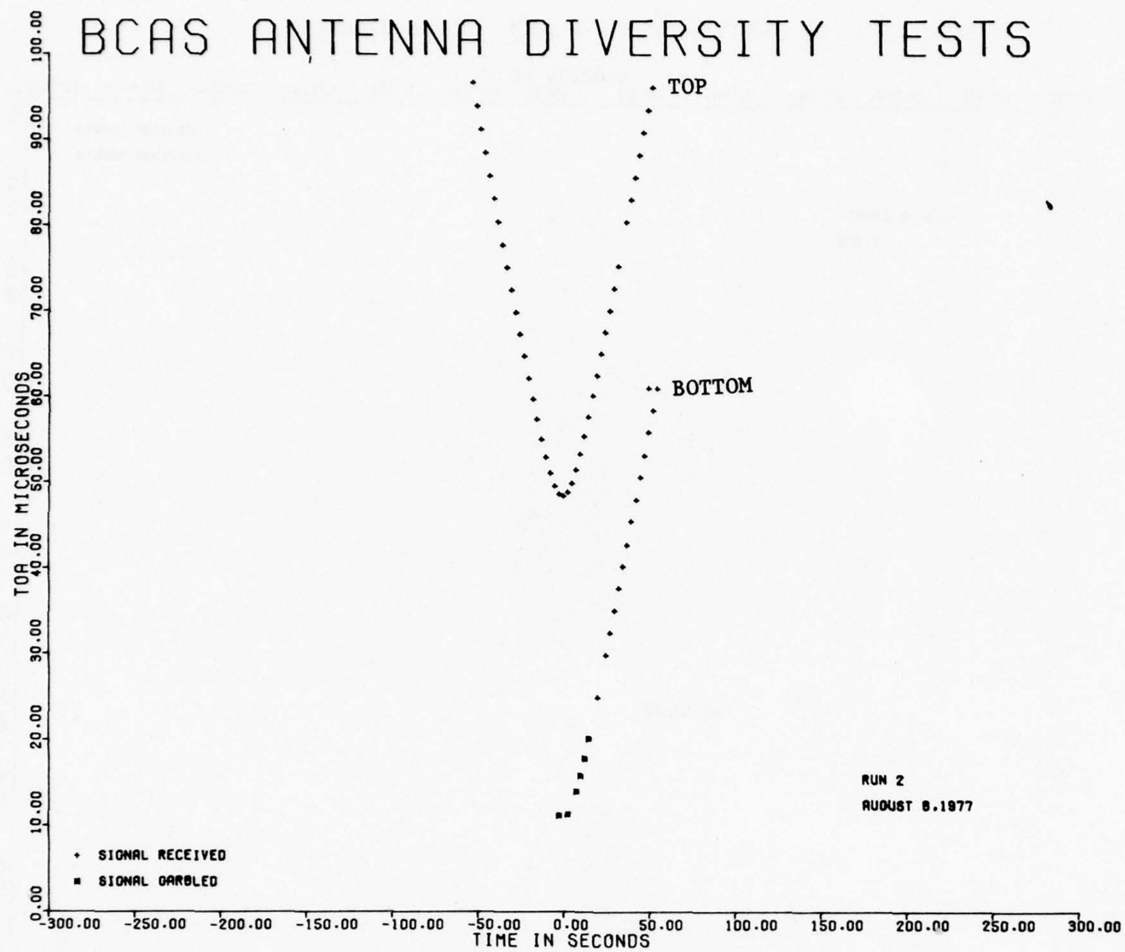


FIGURE 5-6. RUN 2, TOA VALUES

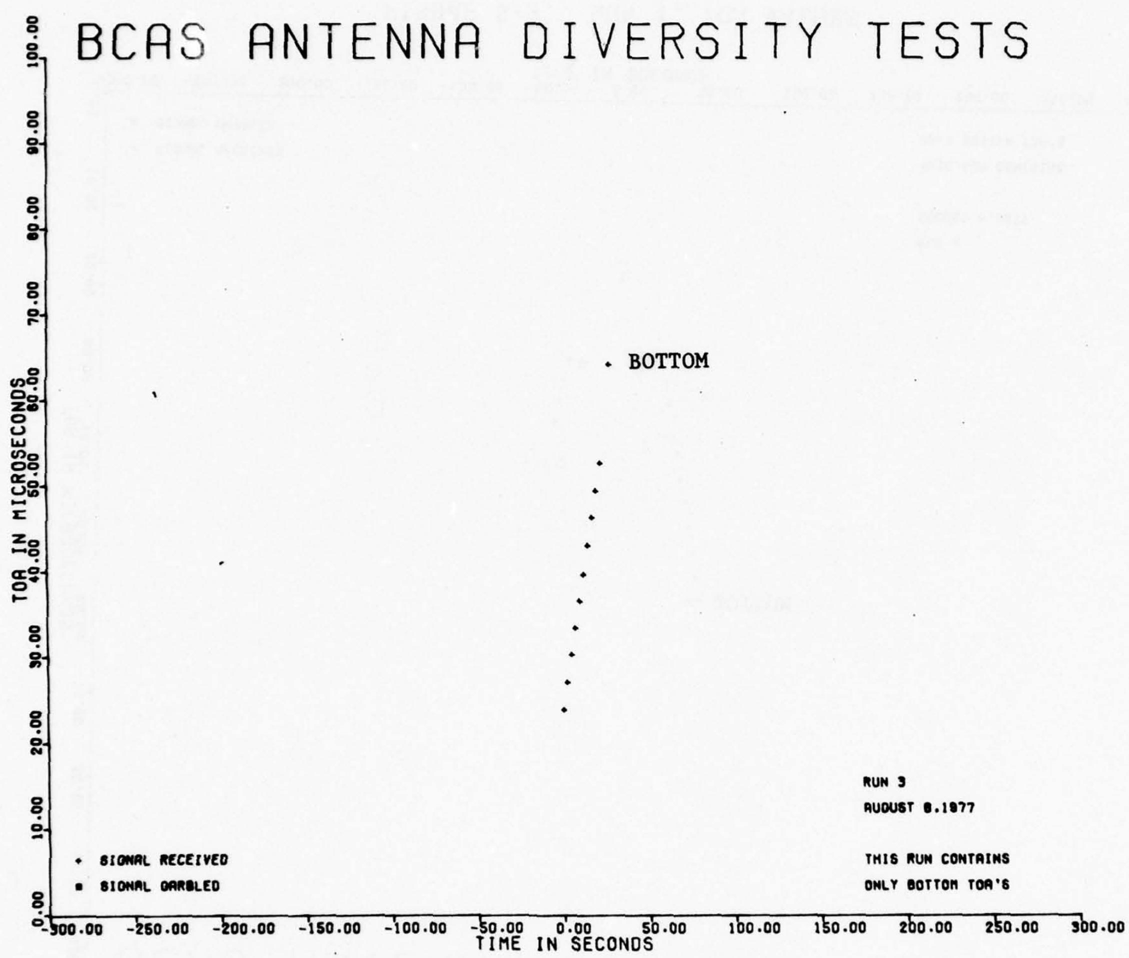


FIGURE 5-7. RUN 3, TOA VALUES

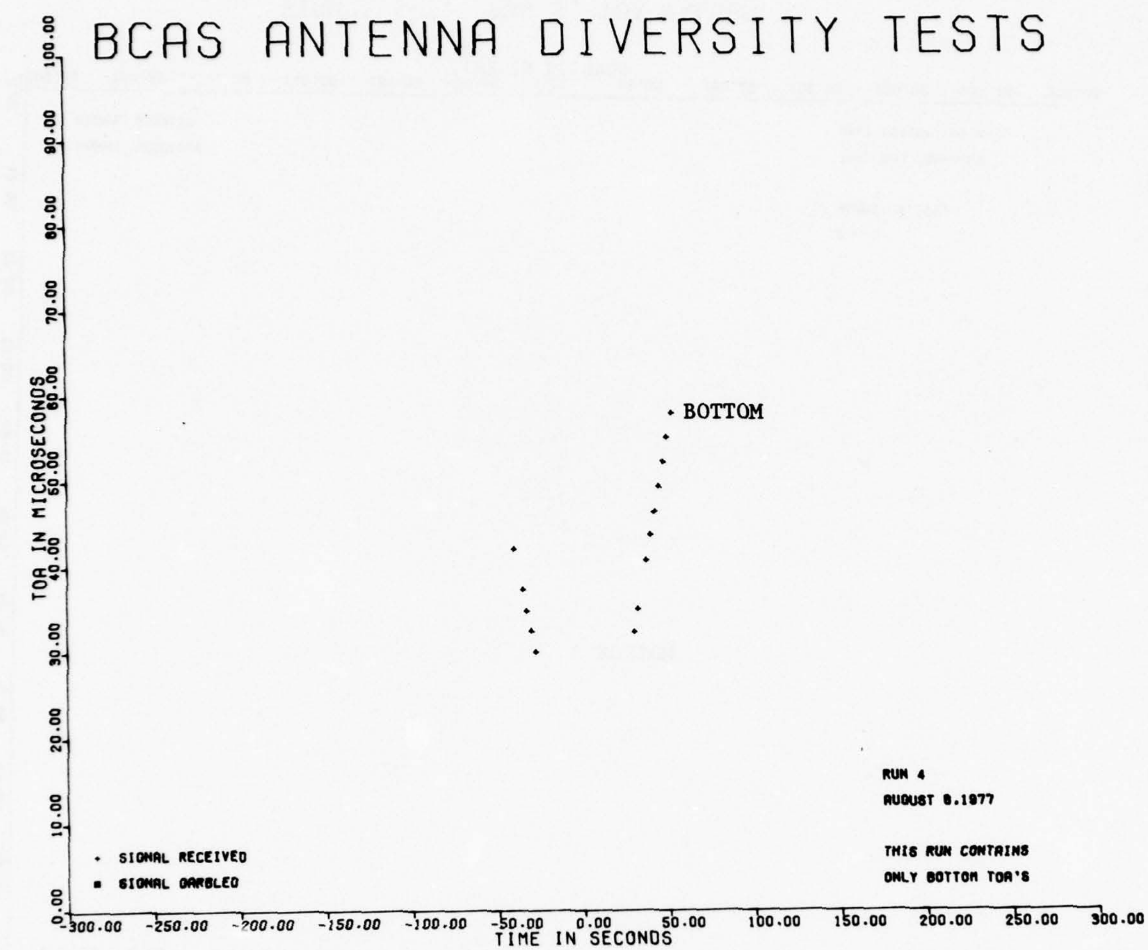


FIGURE 5-8. RUN 4, TOA VALUES

get report printout indicates the presence of two targets with garbled beacon codes which have TOA values and altitude codes consistent with the "bottom" transponder. These occur at 22.1 and 10 seconds prior to crossover for Run 3. Similarly, the target report printout indicates the presence of five targets with garbled identification codes which constitute probable targets for Run 4. These "probable" targets occur in the vicinity of crossover. Figures 5-9 and 5-10 show reliable tracking of the "top" transponder. Tracking of the "bottom" transponder shows a similar tendency to that which was observed in Figures 5-7 and 5-8.

The even-numbered runs (4 and 6) show tracking both before and after corssover while the odd-numbered runs (3 and 5) show tracking after crossover. This effect might be explained by antenna pattern asymmetry if the aircraft were flying with a significant crab angle due to wind. Figure 5-9 shows a single multipath target associated with each transponder.

Figures 5-11 and 5-12 show data for ϕ of 45 degree. As with the previous set, ϕ of 30 degree, the even-numbered run exhibits better tracking of the bottom transponder before crossover, while the odd-numbered run seems to provide slightly better tracking after crossover. It might be pointed out that the relatively large value of the TOA minimum (34.5 microseconds) for the "bottom" transponder is probably indicative of relatively large lack of time coincidence at the cross-over point for Run 7. Since the intended aircraft altitude separation is 2,500 feet, the corresponding TOA minimum for a simultaneous crossover would be 5 rather than 34.5 microseconds actually observed. Multipath targets appear in the data associated with both "top" and "bottom" transponder in Figure 5-12.

Figures 5-13 and 5-14 show data for ϕ of 60 degree. Figure 5-14 shows relatively good tracking of the "bottom" transponder; however, Figure 5-13 shows much poorer performance. Multipath replies can be associated with the "bottom" transponder data.

Figures 5-15 and 5-16, ϕ of 75 degree, show intermittent tracking to the "bottom" transponder both before and after crossover.

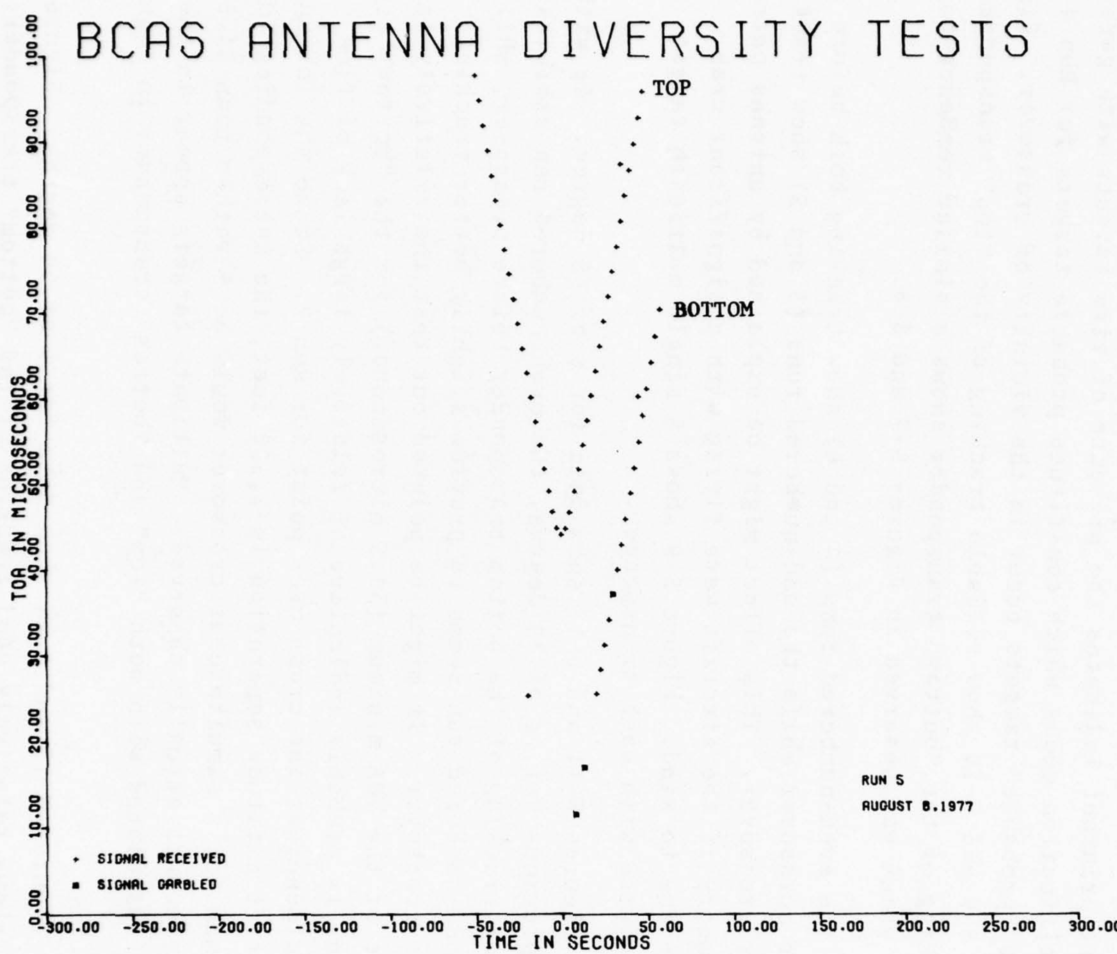


FIGURE 5-9. RUN 5, TOA VALUES

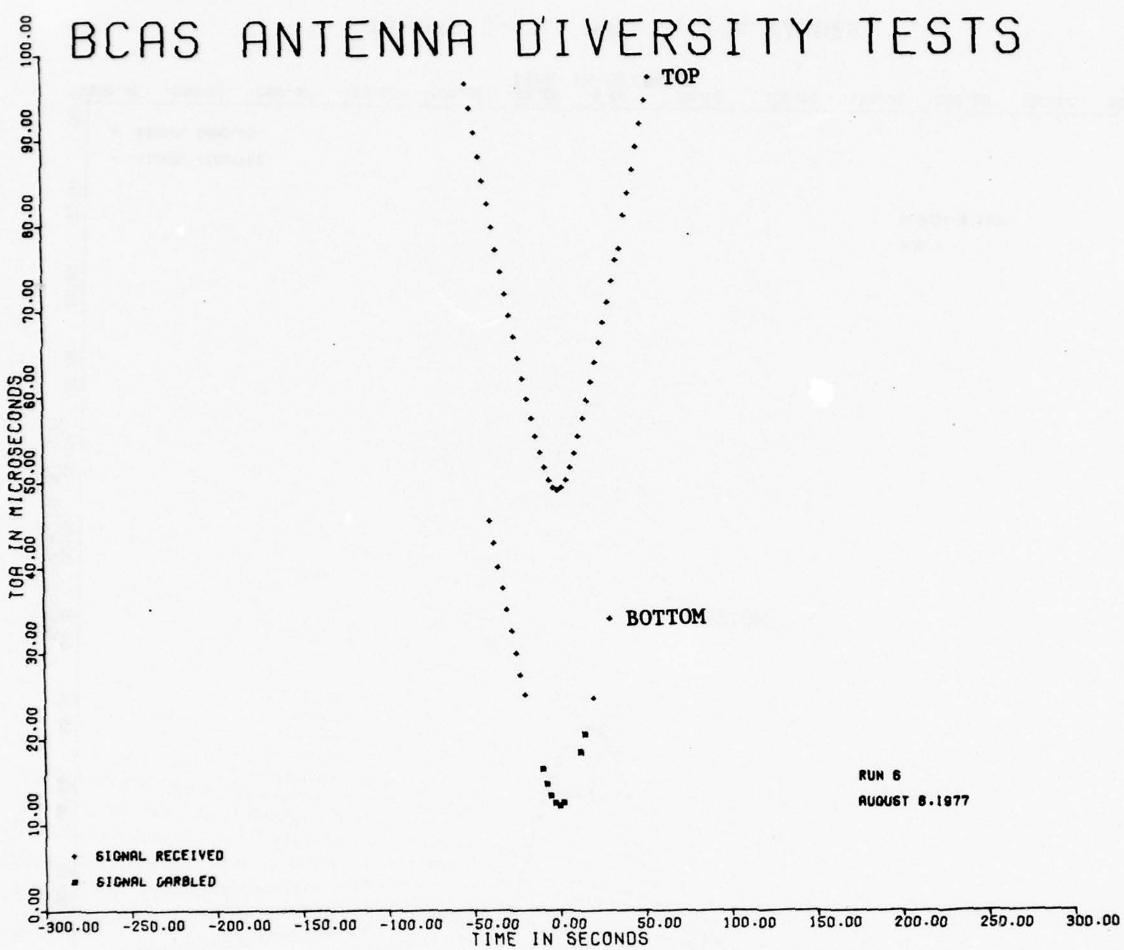


FIGURE 5-10. RUN 6, TOA VALUES.

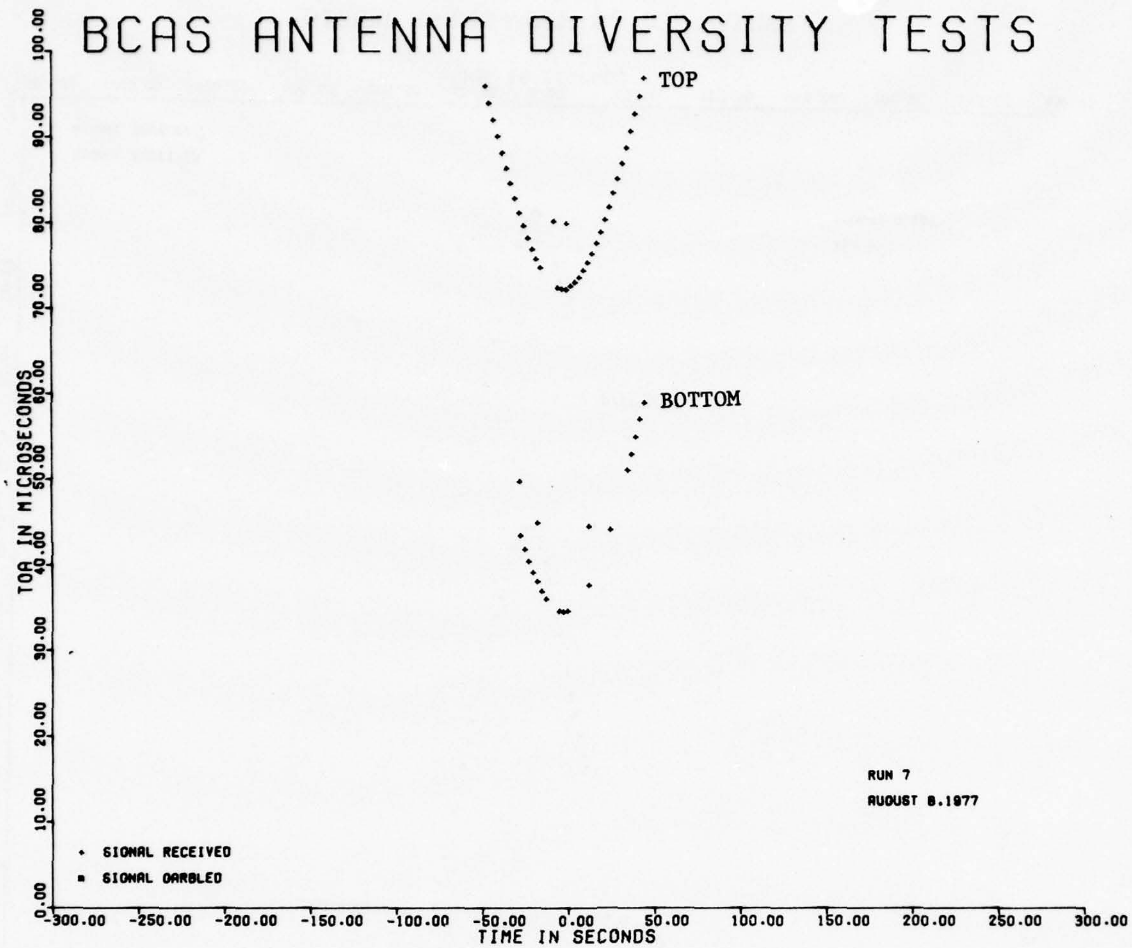


FIGURE 5-11. RUN 7, TOA VALUES.

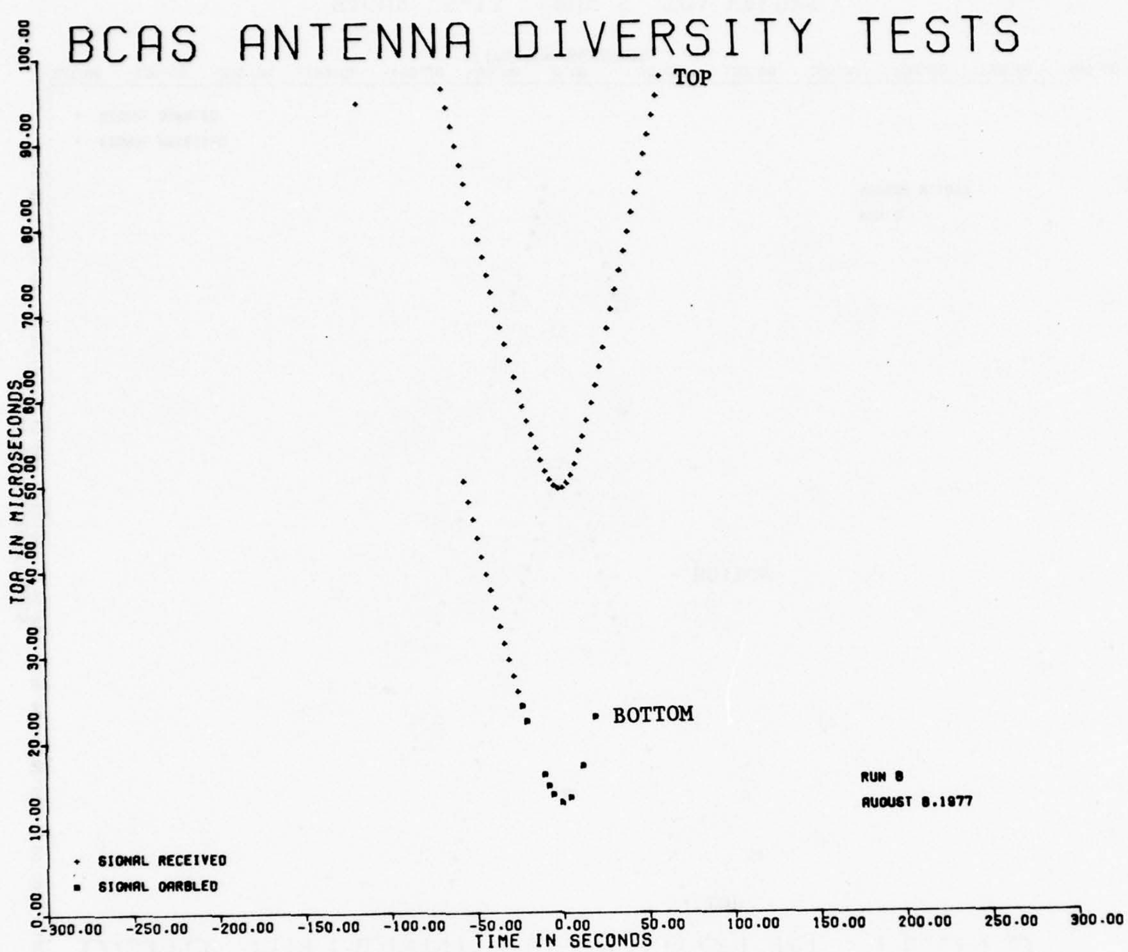


FIGURE 5-12. RUN 8, TOA VALUES.

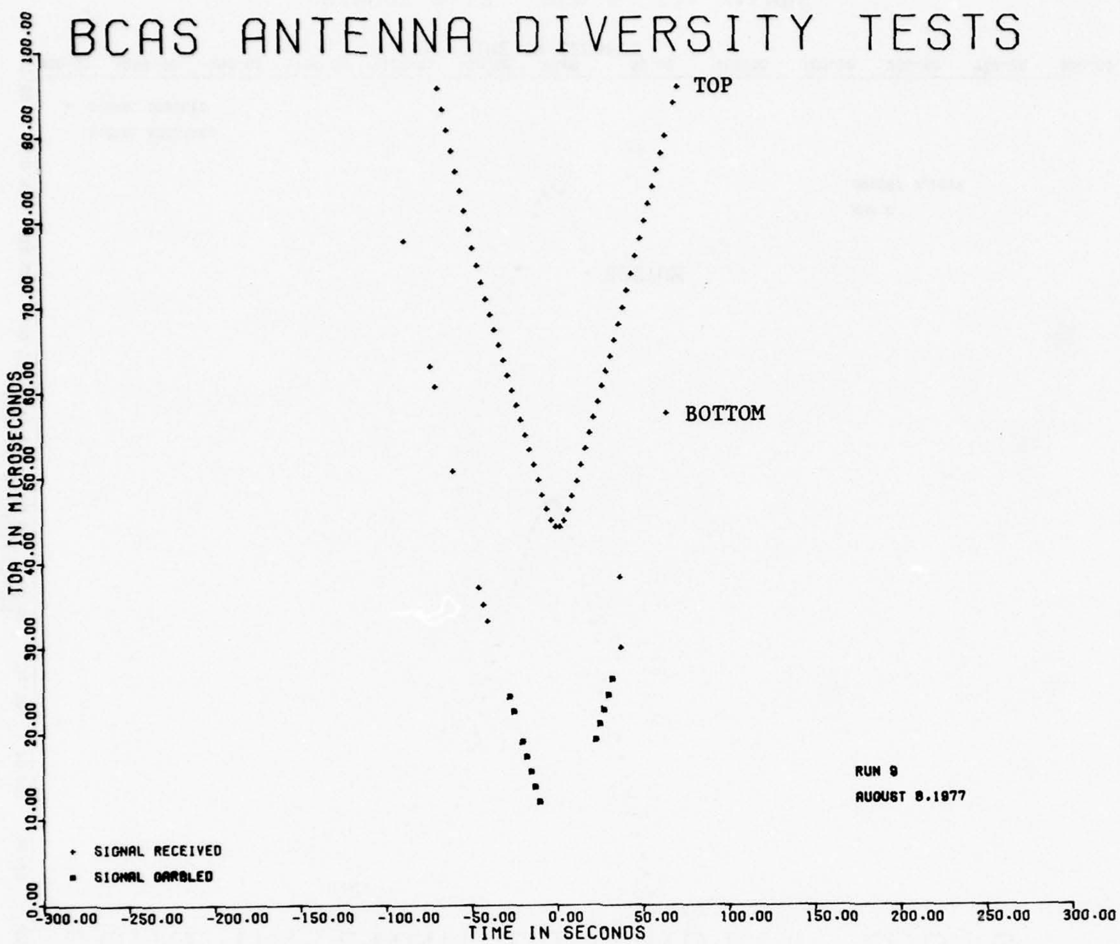


FIGURE 5-13. RUN 9, TOA VALUES

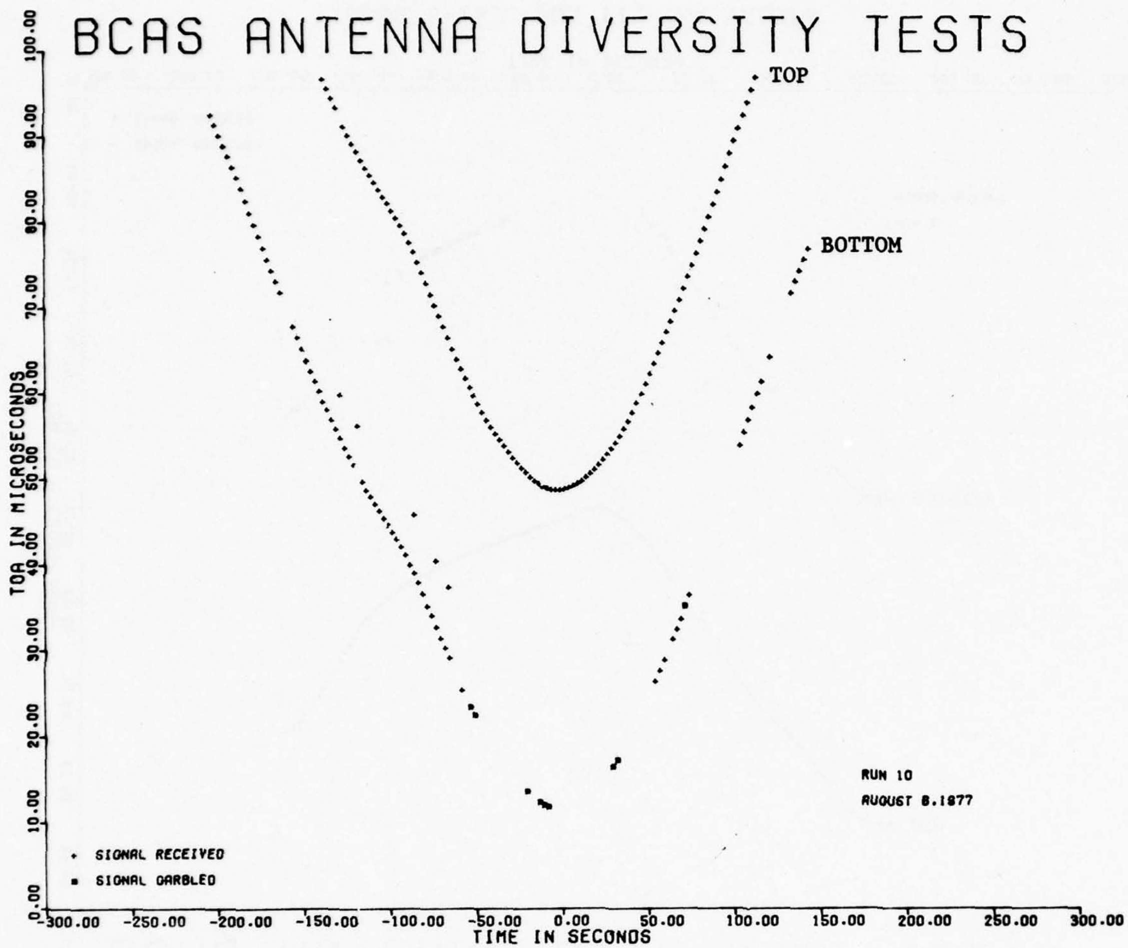


FIGURE 5-14. RUN 10, TOA VALUES

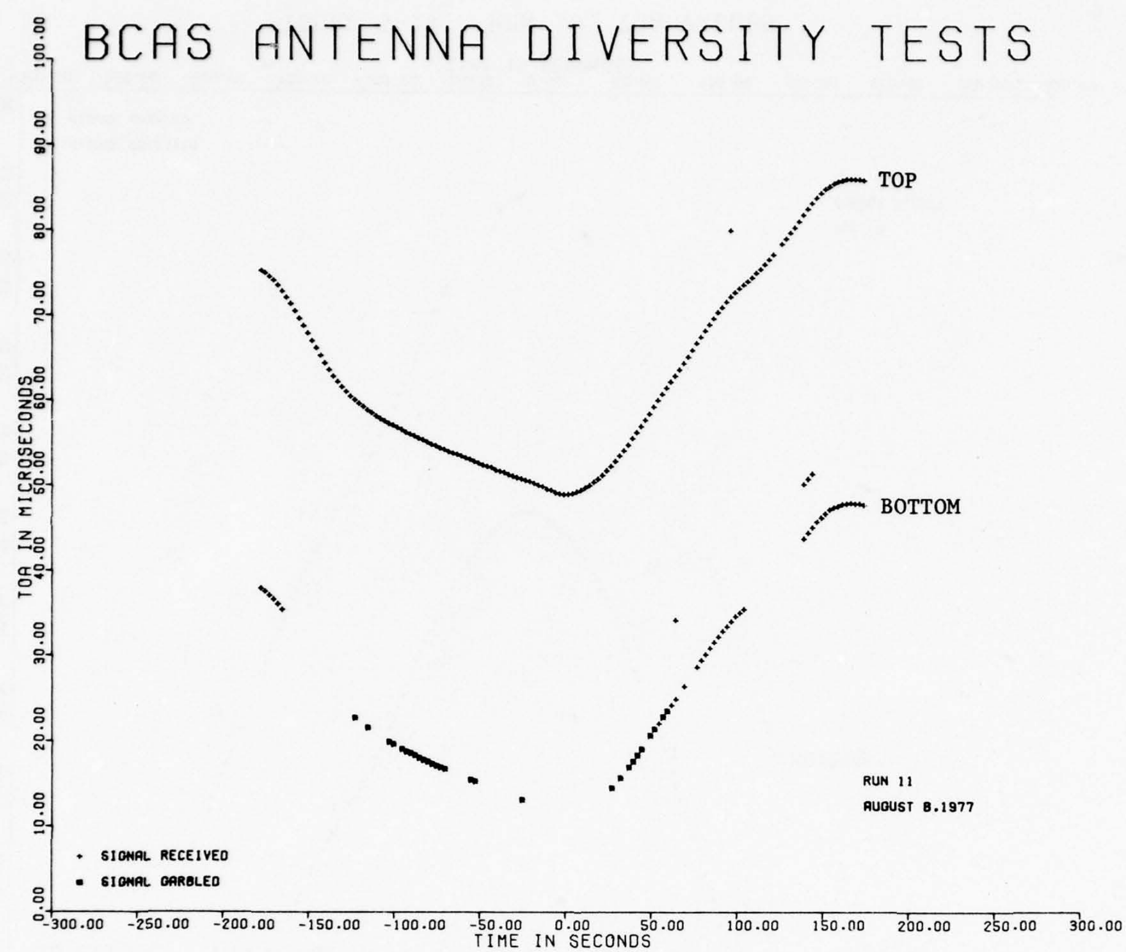


FIGURE 5-15. RUN 11, TOA VALUES

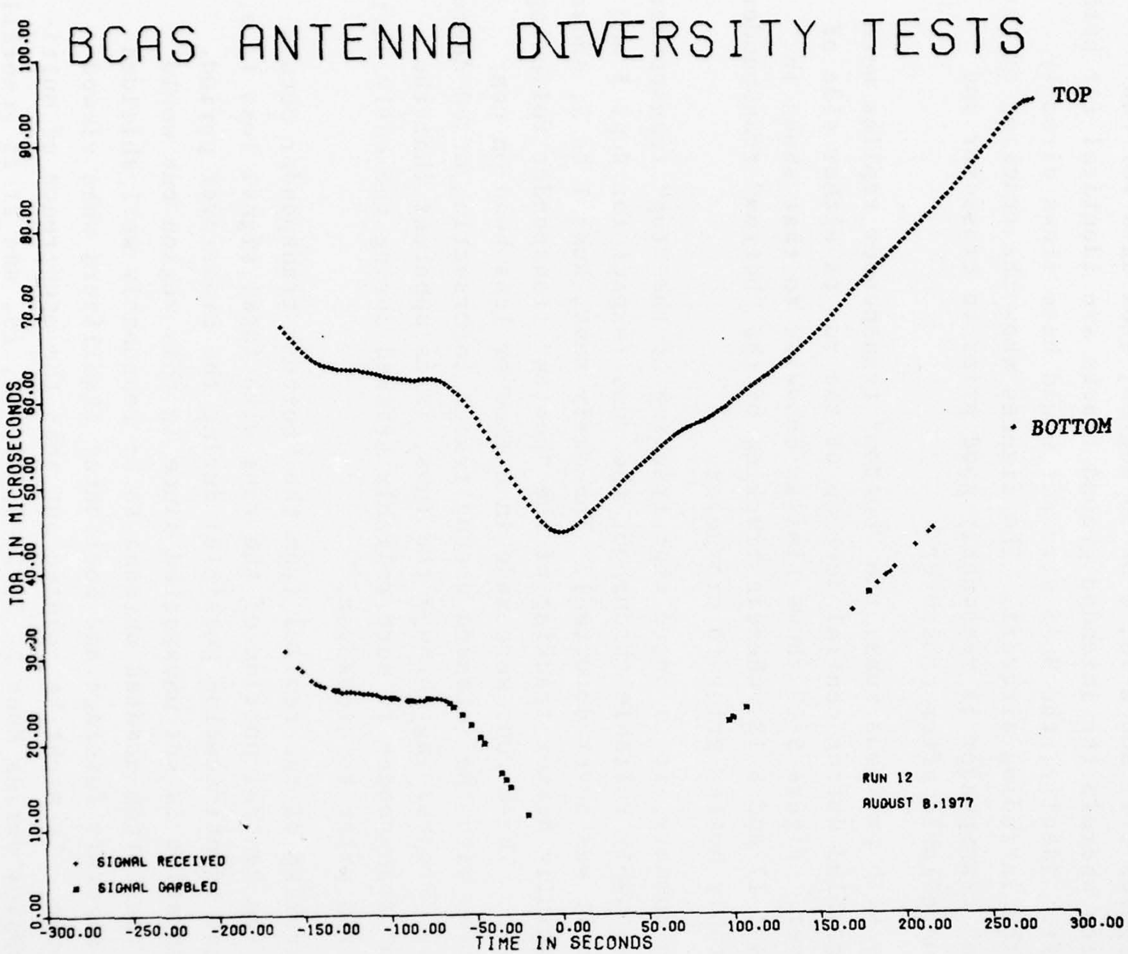


FIGURE 5-16. RUN 12, TOA VALUES

As with previous runs, several garbled replies were received during the central portion of the run. Figure 5-15 shows four multipath replies received by the "bottom" transponder and a single multipath reply from the "top" transponder.

Figures 5-17 and 5-18, ϕ of 90 degree, show data for the situation wherein the intended ground tracks are identical for both aircraft. Ideally, the BCAS aircraft would have flown directly above the intruding aircraft. The figures show the tracking of the "bottom" transponder is reasonably good prior to crossover and quite unreliable after crossover.

As with previous runs, the "bottom" transponder replies were often garbled during central portion of the run on either side of crossover. Figure 5-19 shows similar behavior to that shown in Figures 5-17 and 5-18, wherein tracking of the "bottom" transponder was notably better prior to crossover.

In summary, it is noted that tracking of the "top" transponder was reasonably reliable throughout the runs (expect for Runs 3 and 4 where it was never detected). The early runs, Runs 1 to 5, showed significantly better tracking of the "bottom" transponder following crossover. These runs were made in a more or less head-on configuration with the intended ground tracks intersecting at 60 degree or less. Progressing through the runs, it is apparent that the "bottom" transponder is more reliably tracked during the early part of the run prior to crossover.

Garbling of the replies from the "bottom" transponder occurs during the central portion of the runs with total signal loss (i.e., no target identification possible) during the cross-over period. This situation is not unexpected since in this region one would expect the bottom-mounted antenna to be reasonably well shielded by the aircraft fuselage and horizontal stabilizers when viewed from above. It might be pointed out that the occurrence of multipath replies during Runs 2, 5, 7, 9, 10, 11, 15, and 21 is generally consistent with what one would expect based upon the intended flight geometry.

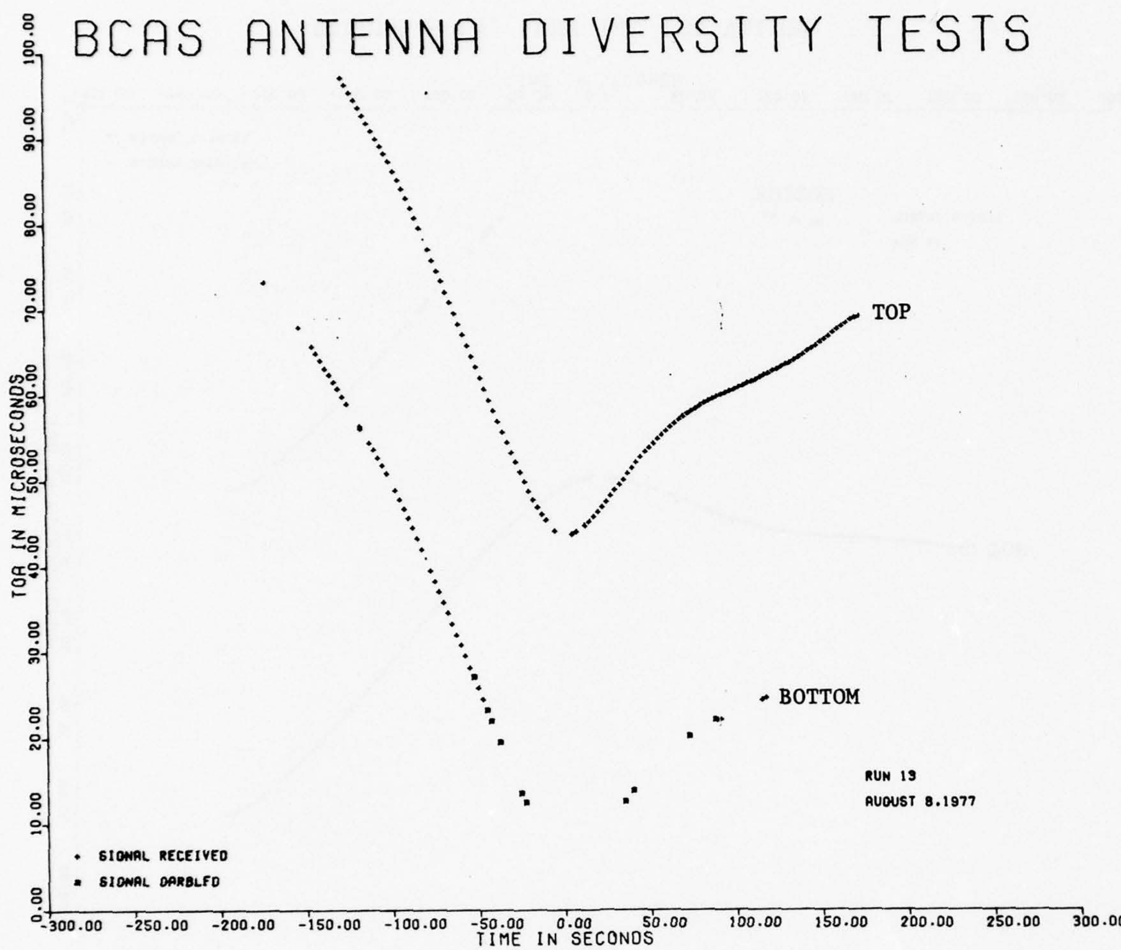


FIGURE 5-17. RUN 13, TOA VALUES

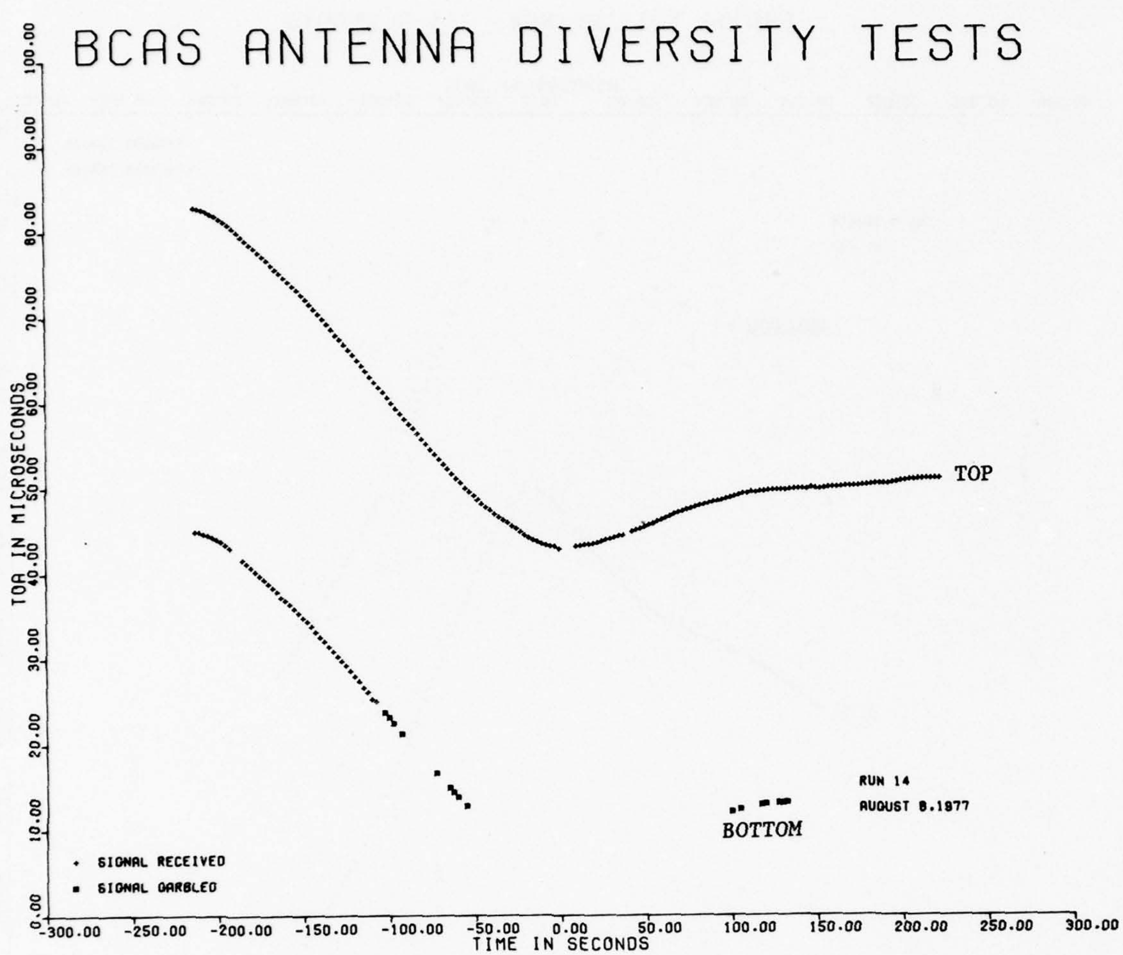


FIGURE 5-18. RUN 14, TOA VALUES

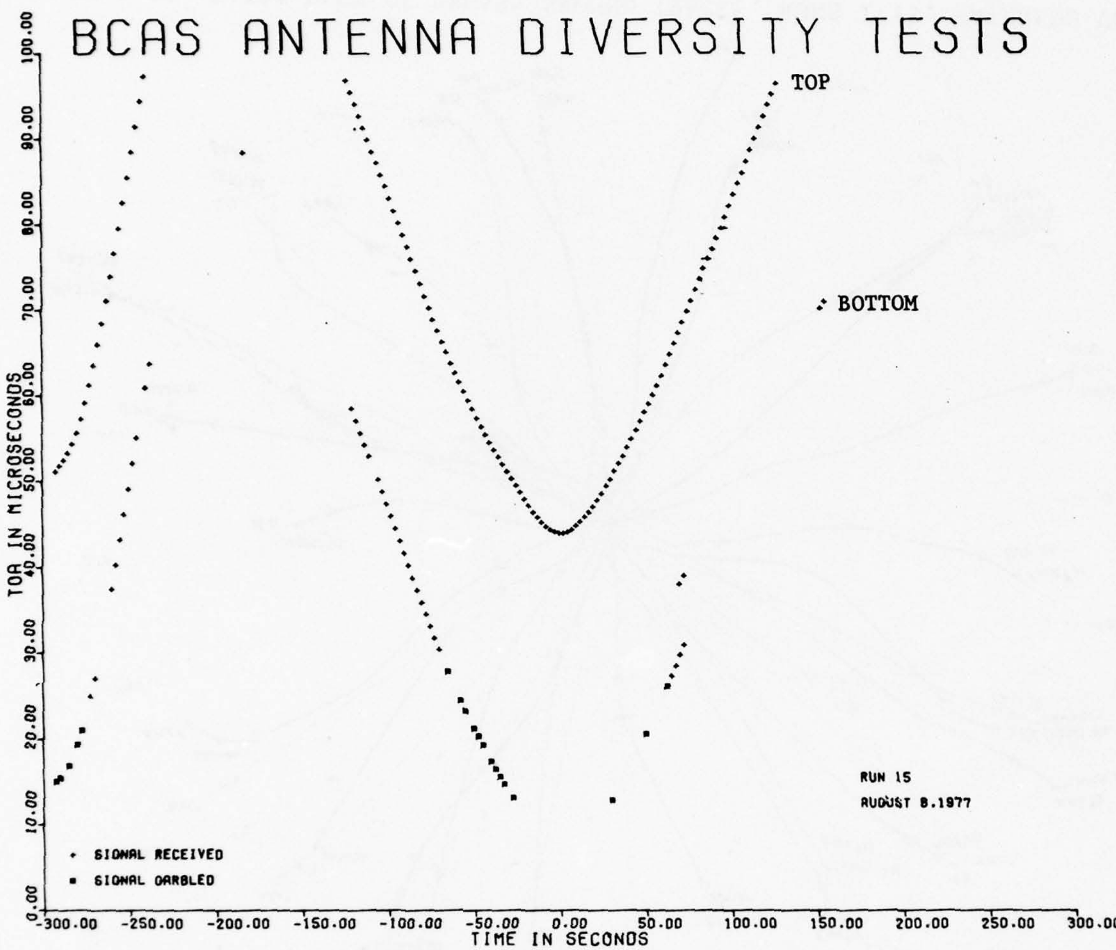


FIGURE 5-19. RUN 15, TOA VALUES

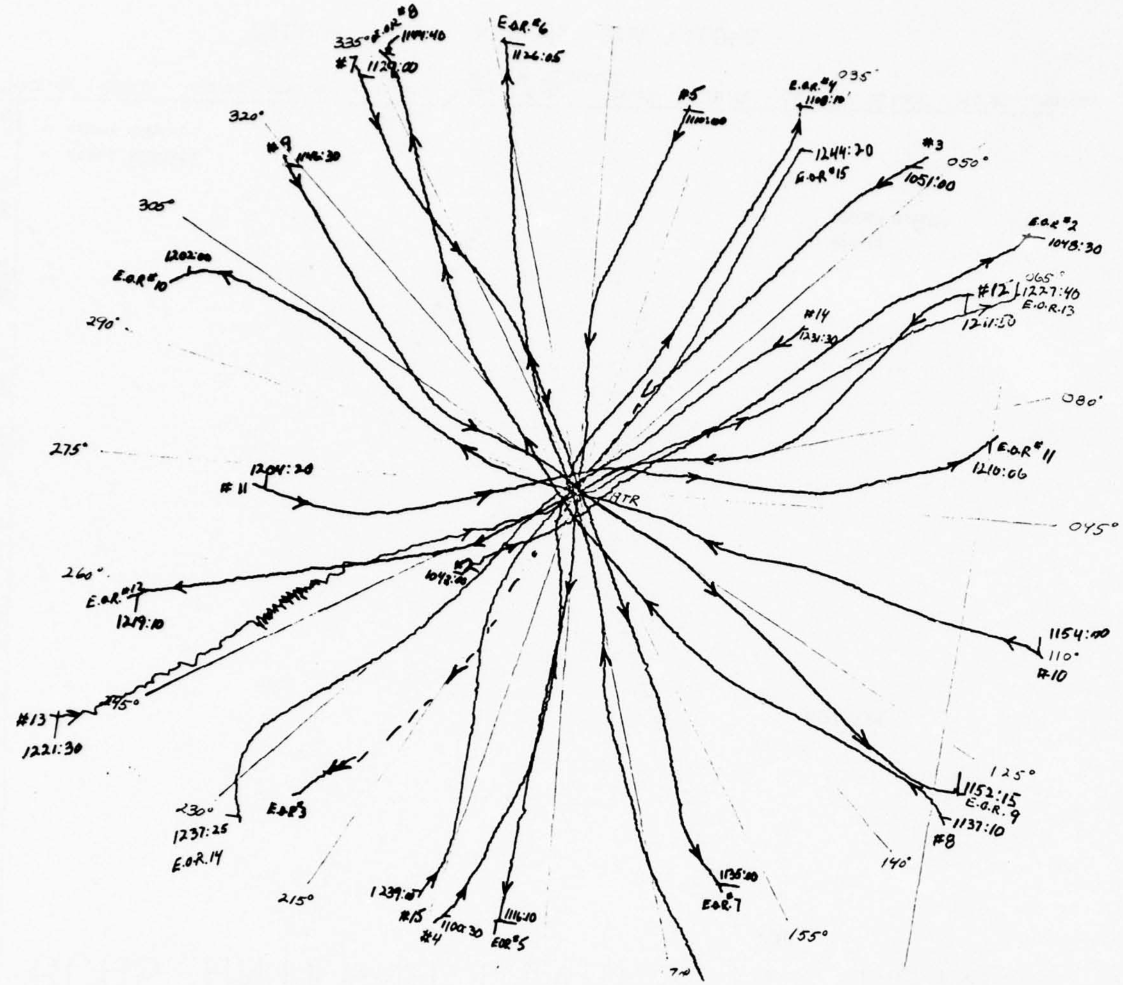


FIGURE 5-20. EAIR* PLOT OF "BCAS" GROUND TRACKS, RUNS 1-15, WATERLOO VORTAC.

* Extended accuracy instrumentation radar

In particular, of the 24 apparent multipath targets identified, all but 5 (which occur in Runs 7 and 21) are found in that portion of the run during which the scattering point is believed to have been over water. Of those five apparent multipath targets, two and possibly more occur close enough to crossover to be explained on the basis of possible deviation from the intended flight geometry.

Figure 5-1 shows the location of the Waterloo VORTAC which is situated very near the west coastline of Delaware Bay. As pointed out in Section 5.1, relatively strong multipath scattering can be expected from a water surface as opposed to that from rural terrain. It should perhaps be pointed out that although the EAIR plots shown in Figure 5-20 indicate the track of the "BCAS" aircraft passing very close to the VORTAC station, there is not way of relating the unusually large TOA minimum of Figure 5-11 to BCAS station passage time.

5.2.2.2 Runs 16 to 24 (Figures 5-21 through 5-37)

Runs 16 through 24 of the daisy over figure eight patterns are considered here in somewhat greater detail since limited position data are available for the intruding aircraft. During these runs, the time and DME readings were recorded on a log sheet for the intruding aircraft (Beechcraft Bonanza). This had been attempted during the morning flight (Runs 1 to 15); however, a high-ambient cockpit light level prevented the technician's reading the digital time display. The ground tracks of the "BCAS" aircraft as determined by the EAIR radar at NAFEC are depicted in the plot shown in Figure 5-21.

Figures 5-22 and 5-23 show the estimated average gain value for the bottom-mounted ATCRBS antenna on the intruding aircraft, taken in the direction to the BCAS aircraft. The estimated gain values are plotted with respect to the time of TOA minimum so as to correspond to the TOA plots. The times of station passage for each aircraft are also shown. These gain values, which are given for each integer nautical mile DME value for the intruding aircraft, are based upon measured flight data obtained by Lincoln Laboratory using their experimental DABS sensor (DABSEF).

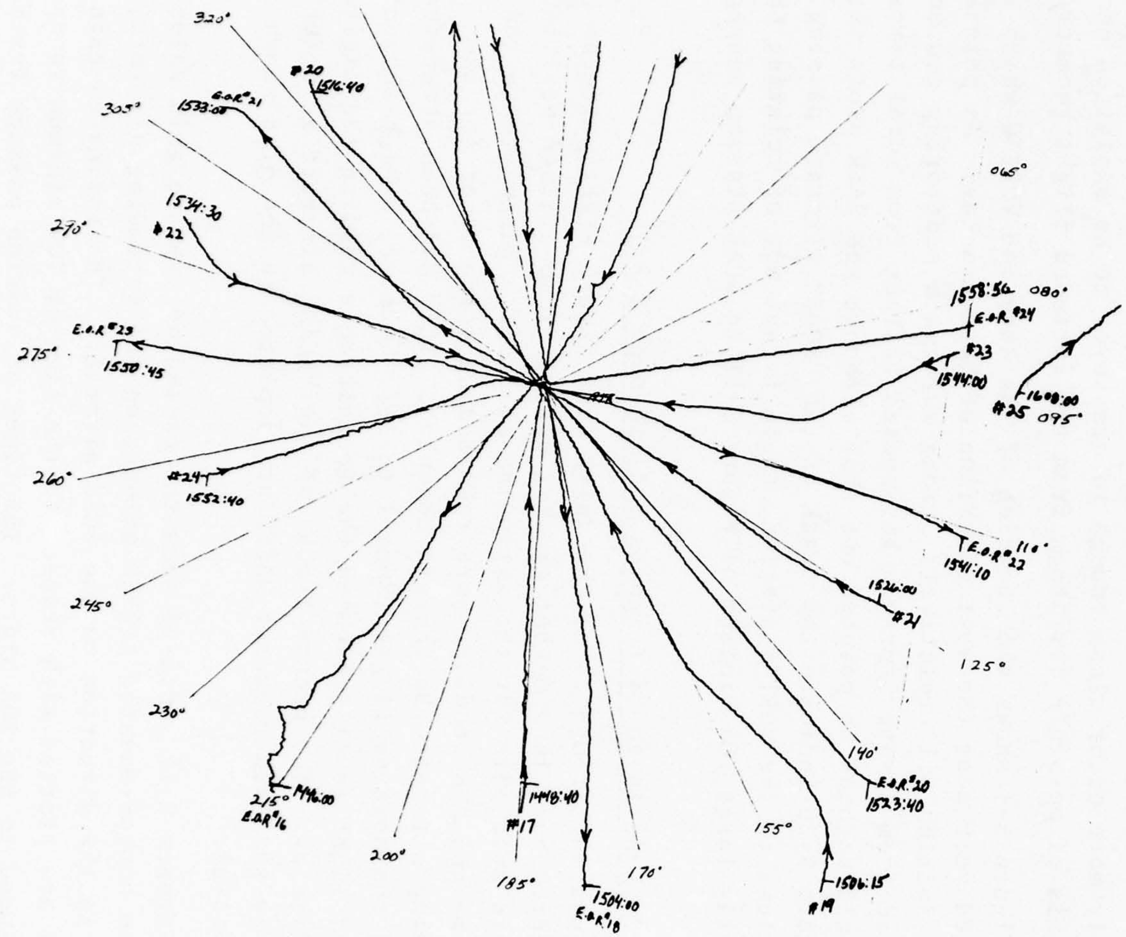
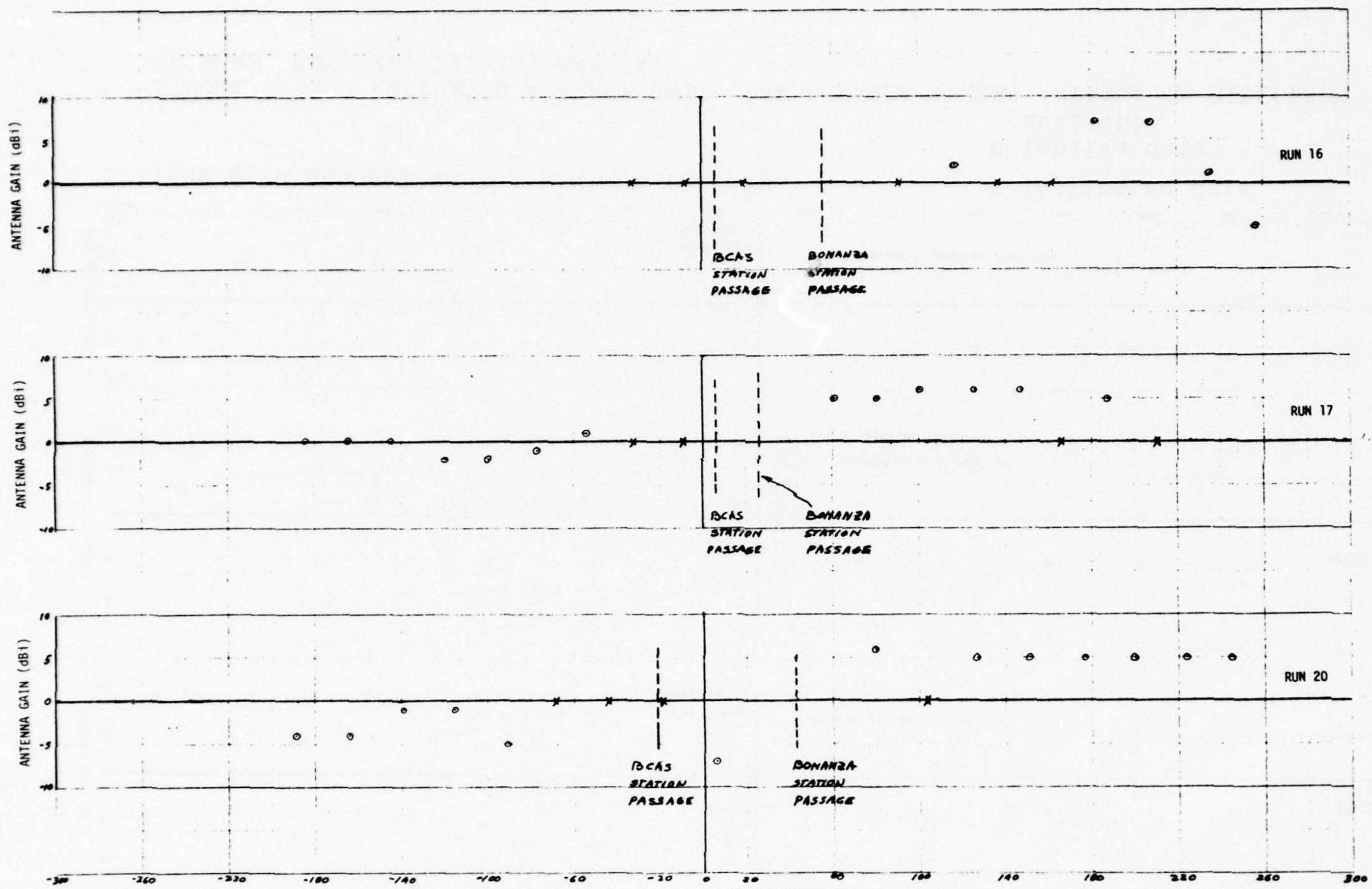


FIGURE 5-21. EAIR PLOT OF "BCAS" GROUND TRACKS, RUNS 16-24, WATERLOO VORTAC



TIME WITH RESPECT TO TOA MINIMUM (SECONDS)

X implies no data

θ implies data available

FIGURE 5-22. ESTIMATED AVERAGE GAIN FOR BONANZA ATCRBS ANTENNA IN DIRECTION OF "BCAS," RUNS 16, 17 AND 20

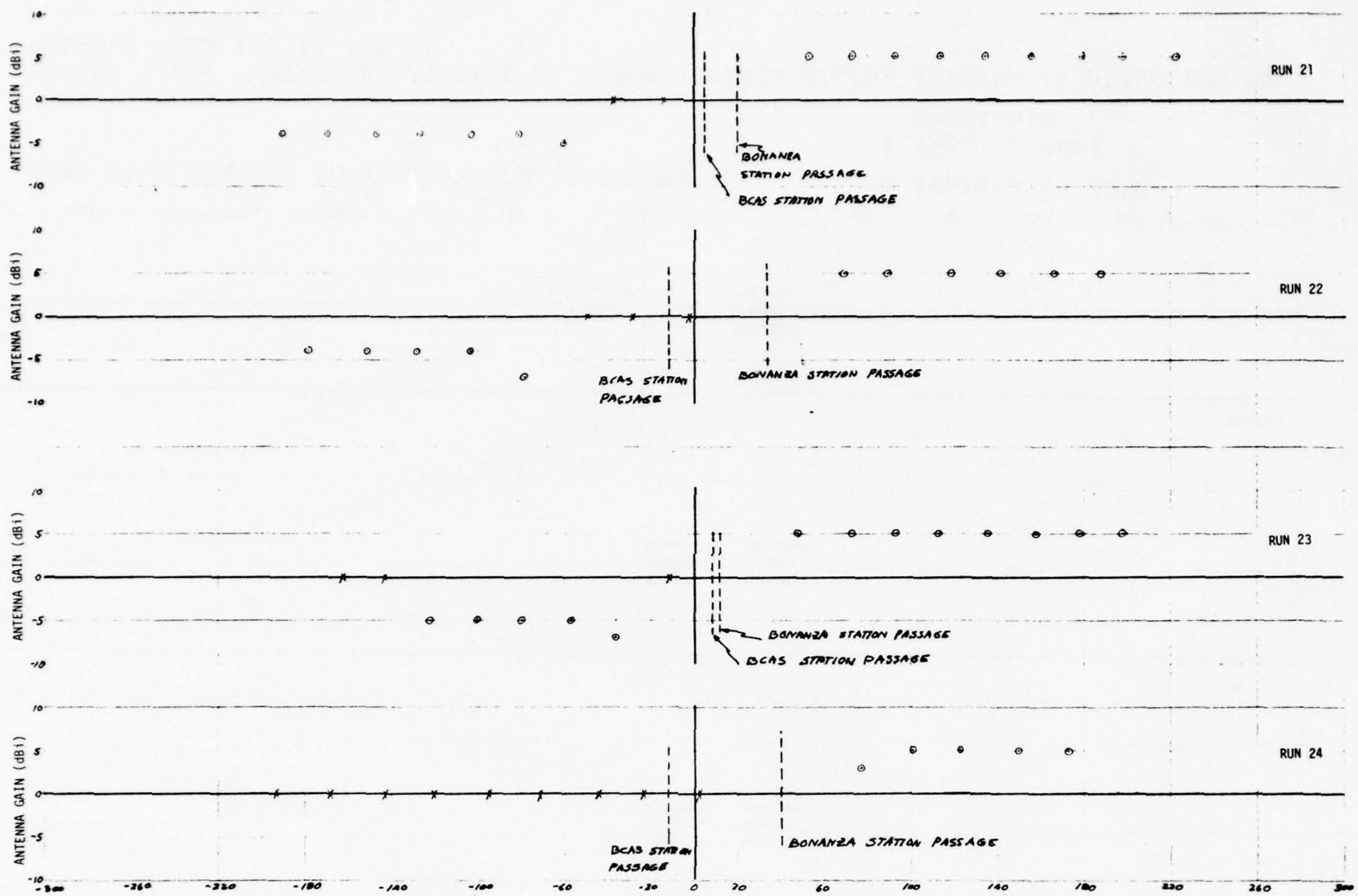


FIGURE 5-23. ESTIMATED AVERAGE GAIN FOR BONANZA ATCRBS ANTENNA IN DIRECTION OF BCAS, RUNS 21, 22, 23, AND 24

The term average refers to the average of the dBi values (i.e., the average of gains of 3 and 7 dBi is taken to be 5 and not 5.45 dBi and hence does not correspond to a power average). The Lincoln Laboratory pattern data are shown in Figures 5-24 and 5-25.

Figure 5-24 shown the "average" gain values for the Bonanza's ATCRBS antenna for measurements corresponding to each cell. The cell size used in these measurements in 6 degree in azimuth and 3 degree in elevation. Figure 5-25 shows the number of measurement samples taken in each cell. A general description of the Lincoln Laboratory measurements can be found in Reference 17 although the data for the ATCRBS antenna which was used in our tests are not contained in Reference 17.

The gain values presented in Figures 5-22 and 5-23 should be considered as presenting only an approximate picture of how the antenna gain varied throughout the various runs. This is due to the fact that the calculation of the relative orientation of the "BCAS" with respect to the intruding aircraft is based upon two rather major assumptions.

The first assumption is that the intruding aircraft was making good its intended ground track during the run, and the second is that the aircraft headings corresponded to those for a no-wind condition. Clearly, neither of these assumptions held exactly, and either or both may have been significantly in error at any given time. The gain values presented in Figures 5-22 and 5-23 are, nevertheless, considered helpful in interpreting the data presented in the TOA plots.

5.2.2.3 Run 16 (Figures 5-26 and 5-27)

Run 16 is the companion to Run 15, both having been flown with intended ground tracks intersecting at 30 degree. Figure 5-26 shows the TOA values for this run during which no target declarations for the "bottom" transponder were made. It appears from the broad TOA minimum (TOA within ± 0.9 μs for 110 sec) shown in Figure 5-26 that the distance between the two aircraft remained relatively constant (i.e., within ± 0.1 nmi) over a nearly 2-minute-long interval in the vicinity of crossover. Examination of Figure 5-21 indicates

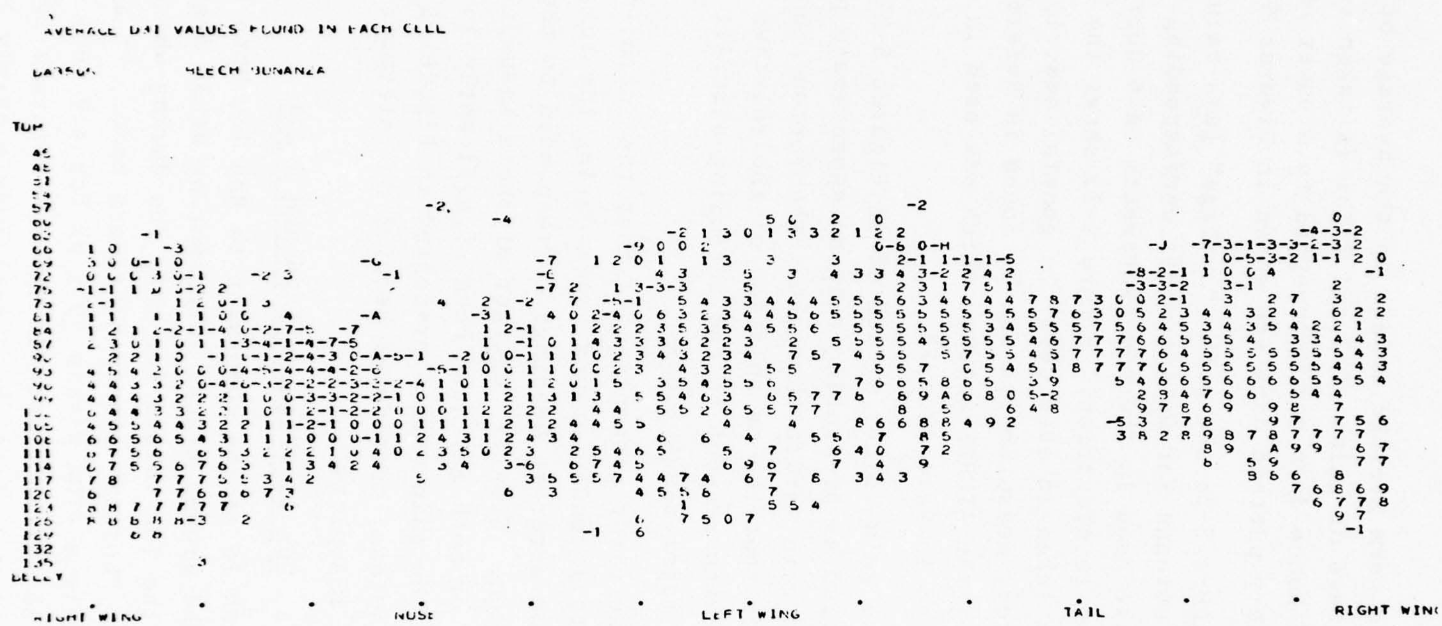


FIGURE 5-24. AVERAGE GAIN VALUES FOR BONANZA ATCRBS ANTENNA (Courtesy: LINCOLN LABORATORY)

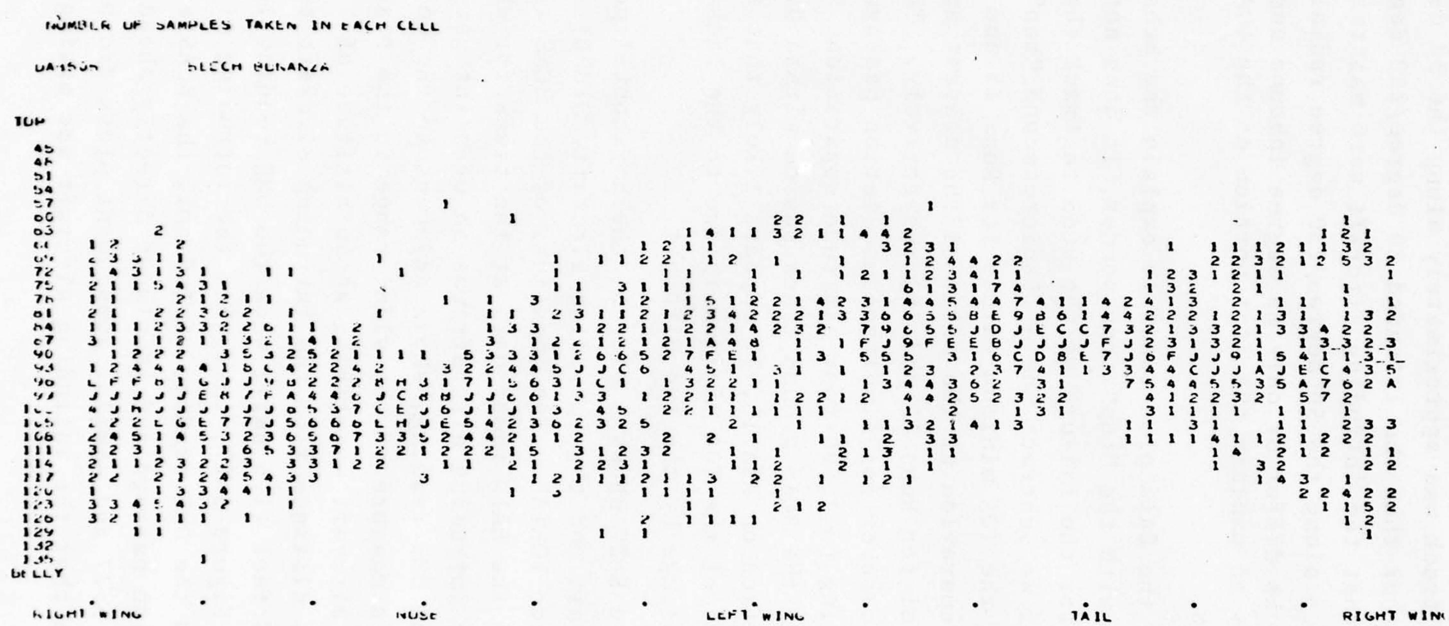


FIGURE 5-25. NUMBER OF SAMPLES TAKEN IN EACH CELL FOR BONANZA ATCRBS ANTENNA (Courtesy: LINCOLN LABORATORY)

that as the "BCAS" aircraft passed through the cross-over region, the ground track was approximately along the 30 degree/230 degree radials rather than the intended 20 degree/200 degree radials. If we assume that the intruding aircraft were maintaining the proper track (i.e., along the 50 degree/230 degree radials), the assumed ground tracks differ by only 20 degree inbound and 0 degree outbound, which tends to explain the flat portion of the TOA curve shown in Figure 5-26.

While the EAIR plot tends to explain the behavior of the TOA associated with the "top" transponder, it does not provide an explanation for the failure of the BCAS to track the "bottom" transponder. If we subtract the 37.5-microsecond "top" transponder delay from the TOA minimum values for Runs 15 and 16, we find that aircraft separation at the point of the nearest approach was 0.68 and 1.48 nmi for Runs 15 and 16, respectively. The "ideal" separation at crossover for simultaneous station passage is 0.41 nmi corresponding to 2,500-foot altitude separation. Since the EAIR radar shows the BCAS ground track passed within 0.2 nmi of the VORTAC station on Run 16, it appears likely that the relatively large value of the TOA minimum is due to the lack of simultaneous station passage by the two aircraft.

Figure 5-27 shows a plot of the horizontal positions of the BCAS aircraft and the intruding aircraft (OTHER) with respect to the Waterloo VORTAC. The locations of the BCAS aircraft are taken from the EAIR radar data at the times for which the DME reading of the intruding aircraft was an even integer of nautical miles. The DME reading, shown adjacent to the corresponding data point, is a measure of the slant range to the station. Since the intruding aircraft was flying at an altitude of 7,000 feet, the horizontal distance from the intruding aircraft to the station is only 9,933 feet (1.6 nmi), when the DME reading is 2.0 nmi. We note from Figure 5-27, that when the intruding aircraft is inbound with the DME reading of 2.0 nmi, the BCAS aircraft has just made station passage and is almost directly ahead. The plot shown in Figure 5-27 and similar subsequent plots are based upon the assumption that the intruding aircraft was making good its intended

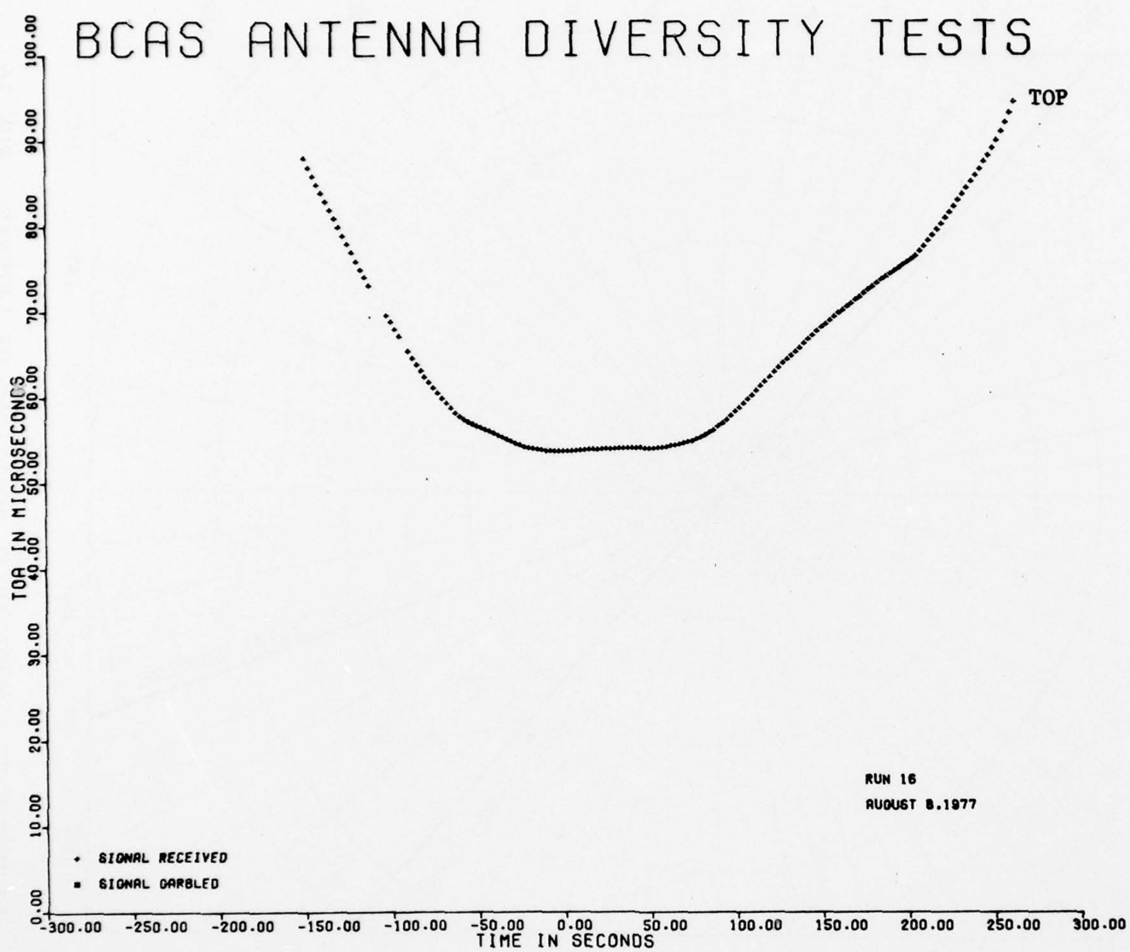
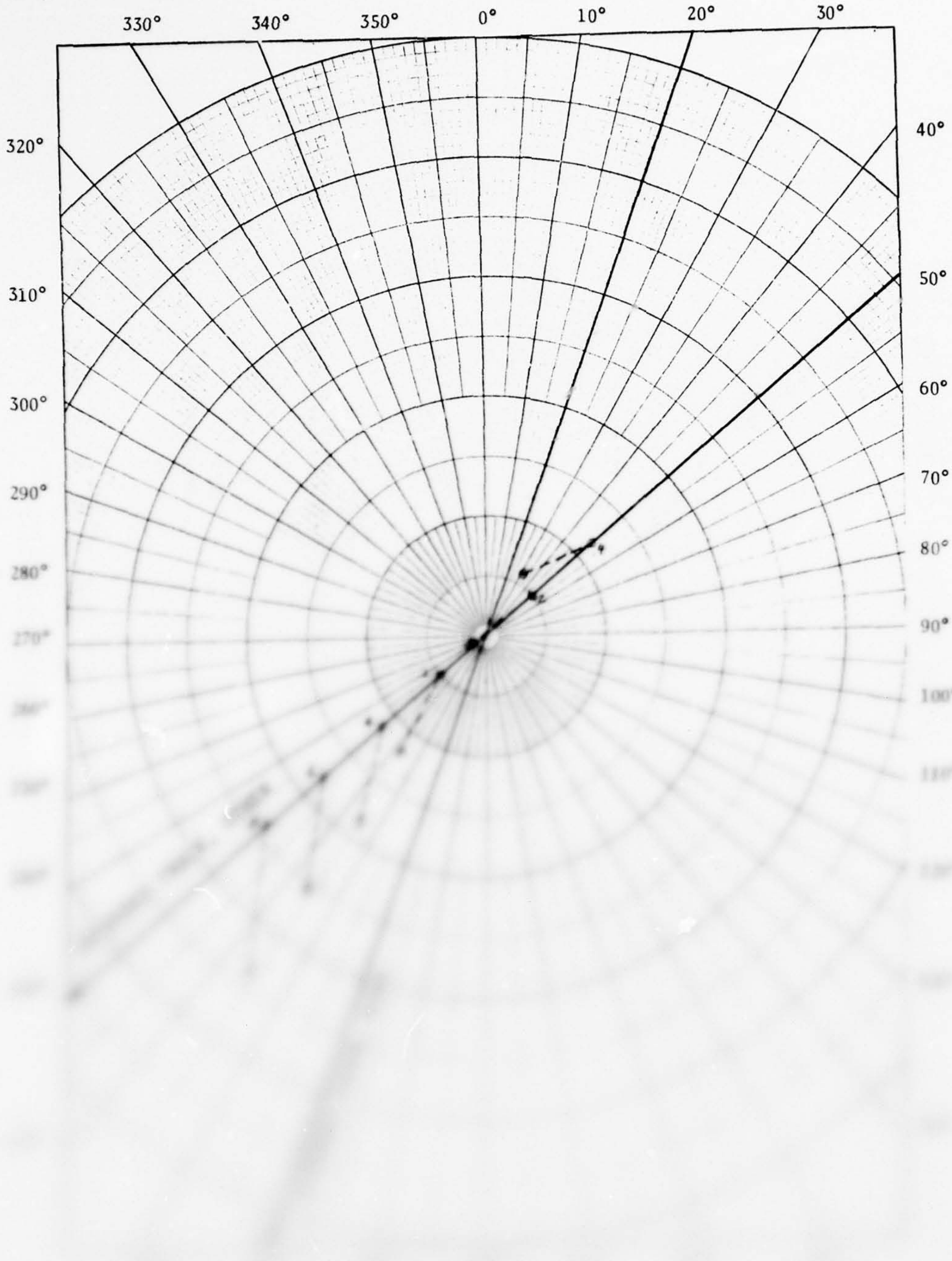


FIGURE 5-26. RUN 16, TOA VALUES


330°
340°
350°
0°
10°
20°
30°
320°
40°
310°
50°
300°
60°
290°
70°
280°
80°
270°
90°
100°

ground track.

It will be noted that only five estimated gain values are presented in Figure 5-22. The missing values, indicated by crosses, correspond to cells for which no gain values were measured. It is unfortunate that so few gain values were available for this run during which no "bottom" transponder target replies could be identified. In particular, there are no gain values for the region of lost targets prior to TOA minimum. To summarize, the behavior of the TOA values for the "top" transponder is explainable on the basis of flight geometry. No adequate explanation for the failure to track the "bottom" transponder was found.

5.2.2.4 Run 17 (Figures 5-28 and 5-29)

Run 17 was flown with an intended ground track intersection angle of 60 degree. Figure 5-28 shows the tracking of both "top" and "bottom" transponders. Tracking of both transponders was reasonably reliable except for an interval of approximatley one minute in duration occurring just prior to crossover. Aircraft separation at initial target declaration was 4.5 nmi and at final target declaration was 4.8 nmi. Faulty* tape records during the one-minute lost-time interval prevented evaluation of the system during this portion of the run. Unfortunately, the companion run, Run 18, produced only four target declarations, and hence provides little information concerning what may have taken place during this interval.

The horizontal positions of the two aircraft are shown with [illegible]

[illegible]

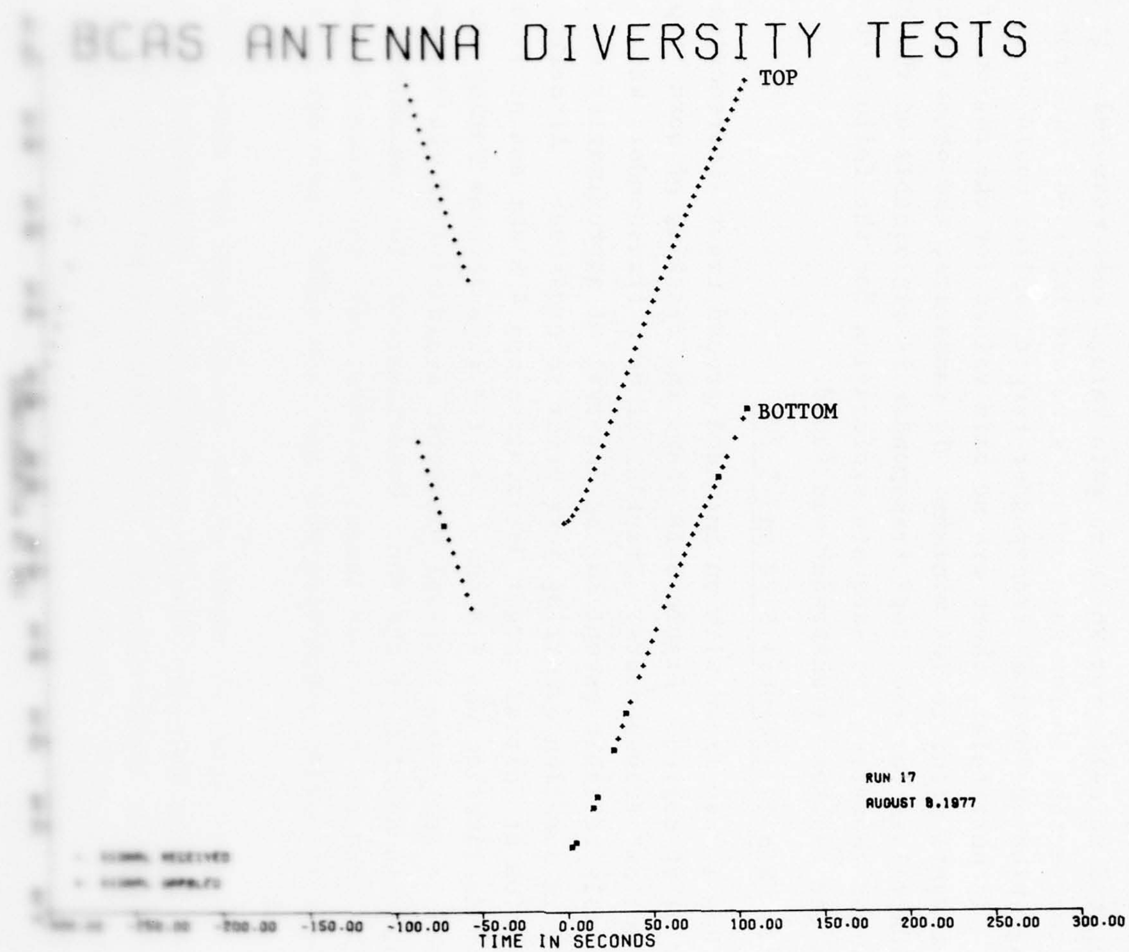
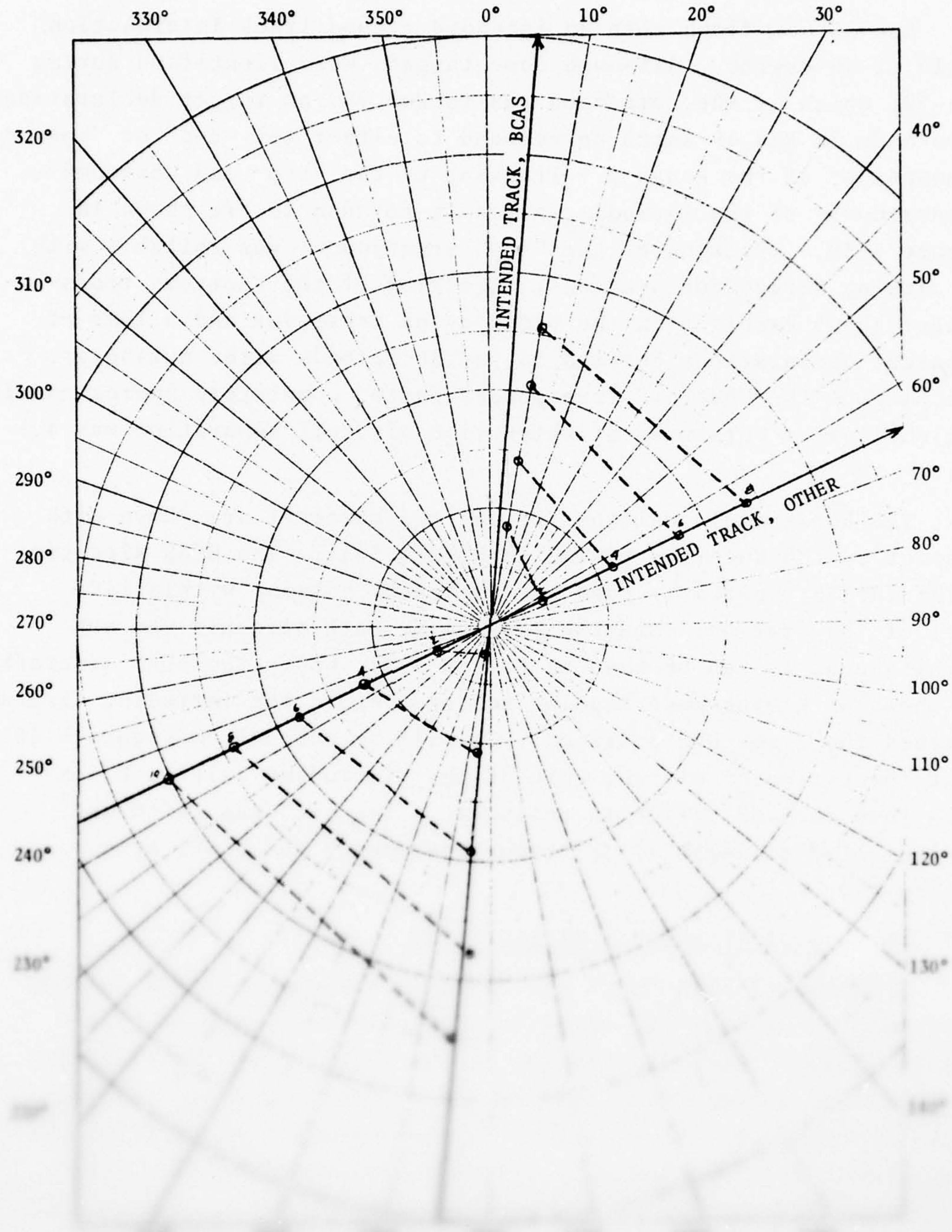


FIGURE 5-28. RUN 17, TOA VALUES



[illegible] HORIZONTAL POSITIONS OF AIRCRAFT, RUN 17, [illegible]

5.2.2.5 <u>Run 20 (Figures 5-30 and 5-31)</u>

Run 20 was flown with an intended ground track intersection angle of 90 degree. Although some targets were identified during Run 19, which is the companion run to Run 20, no target declarations were made in Run 19 which correspond to either the "top" or "bottom' transponder of the Bonanza. Tracking of the "top" and "bottom" transponders of the intruding aircraft for Run 20 are shown in Figure 5-30. Tracking of the "top" transponder was reliable with no missing target declarations. Tracking of the "bottom" transponder shows garbling in the vicinity of crossover and a loss of 5 target declarations between 35 and 50 seconds after corssover. Tracking of the "bottom" transponder failed completely approximately 1 minute after corssover at which time aircraft separation was 4.5 nmi.

The horizontal positions of the two aircraft are shown with respect to the Waterloo VORTAC in Figure 5-31. The BCAS aircraft maintained a reasonably good ground track, passing within 147 feet of the station. Station passage by both aircraft was not simultaneous as can be seen in Figure 5-31, where the BCAS aircraft is shown as having made station passage before the intruding aircraft reached the 2-nmi DME position. It will be noted from Figure 5-22 that the estimated antenna gain of the "intruding" aircraft was less than zero dBi prior to crossover. The gain was (with the exception of a single -7-dBi value) between 5 and 6 dBi after crossover.

5.2.2.6 <u>Run 21 (Figures 5-32 and 5-33)</u>

Tracking of both "top" and "bottom" transponders was reasonably good during Run 21. As with previous runs, garbled target identification codes are evident in the vicinity of crossover for the "bottom" transponder. The "bottom" transponder was tracked from 50 seconds before crossover to approximatley 60 seconds after crossover. The corresponding aircraft separations were 4.1 and 5.6 nmi, respectively. A single multipath target can be seen associated with the "bottom" transponder near the end of the run. The

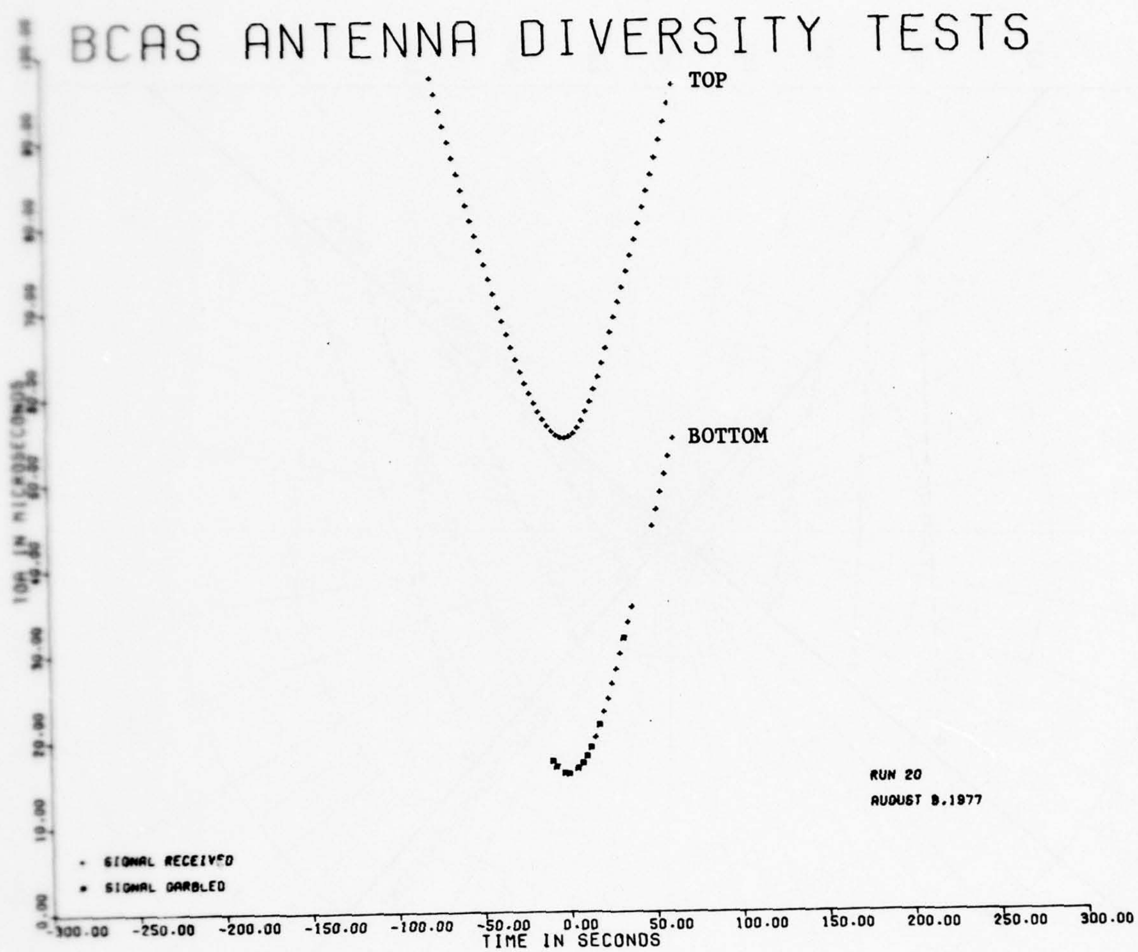


FIGURE 5-30. RUN 20, TOA VALUES

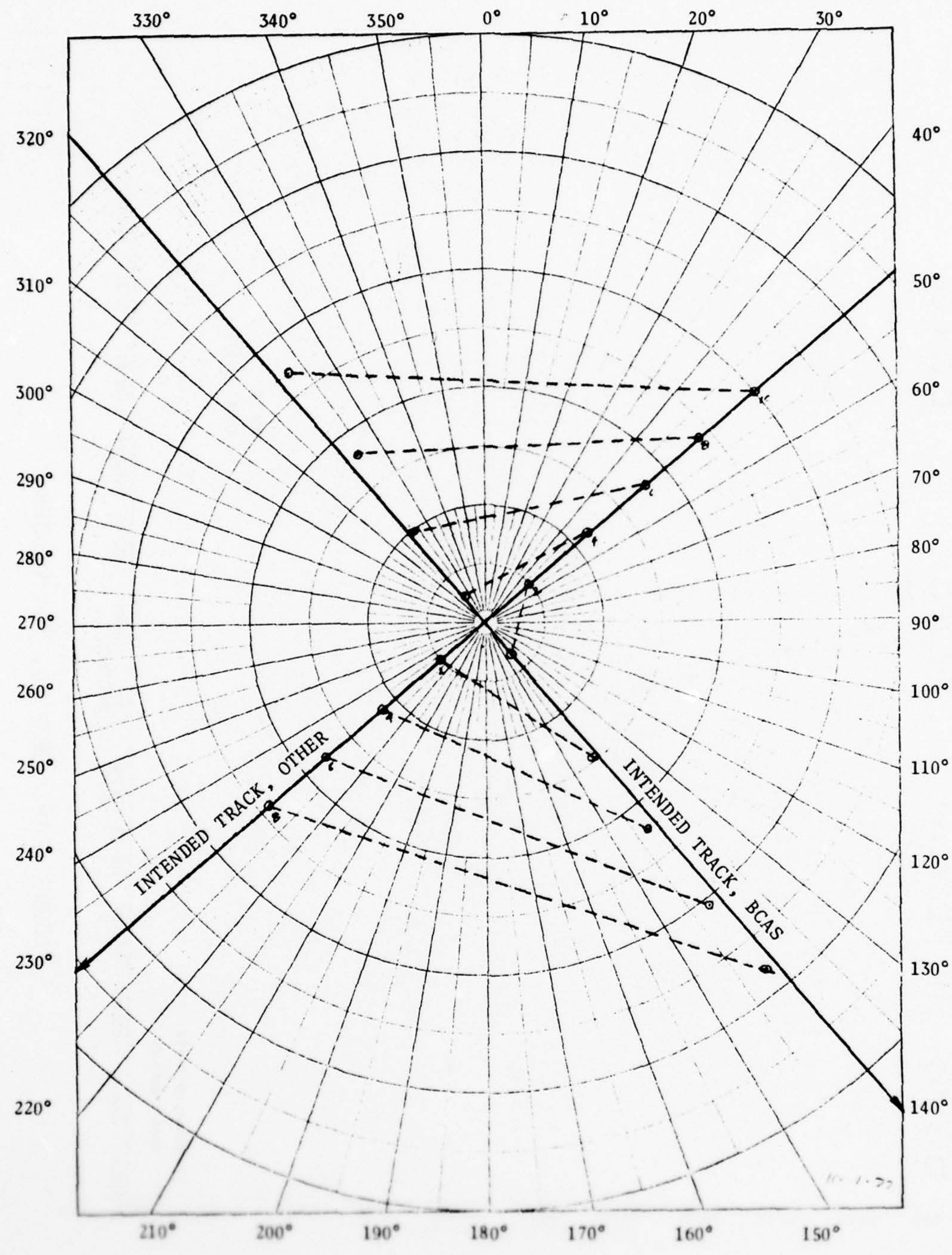


FIGURE 5-31. HORIZONTAL POSITIONS OF AIRCRAFT, RUN 20, WATERLOO VORTAC

measured multipath delay is 4.84 microseconds; a calculated value of 5.95 microseconds is based upon the assumption that the intruding aircraft is making good its intended ground track (Fig. 5-32).

Referring to Figures 5-1 and 5-33, we note that the multipath scattering on the outbound leg is from the ocean surface (approximately along the 005 degree radial) from which relatively strong signal returns can be expected. Figure 5-23 shows the estimated antenna gain values corresponding to Runs 20 through 24. We note that antenna gian values of -4 and -5dBi were encountered prior to crossover. The gain value associated with the outbound portion of the run was 5 dBi. Although the system maintained target declaration to 5.6 nm outbound (initial target declaration at 4.1 nmi inbound), the path loss difference corresponds to less than 3 dB rather than to the nearly 10-dB antenna gain difference shown in Figure 5-23. The trend at least is in the right direction with the higher gain values associated with the greater tracking distance.

5.2.2.7 Run 22 (Figures 5-34 and 5-35)

Run 22 is the companion run to Run 21. Unlike Run 21 wherein the "bottom" transponder was tracked both inbound and outbound, Figure 5-34 shows tracking on the outbound leg only for Run 22. We note from Figure 5-35 that the BCAS aircraft had made station passage prior to the intruding aircraft's (the Bonanza's) having reached the inbound 2.0-nmi DME position. The situation tends to place the BCAS aircraft over the nose of the Bonanza where the antenna gain is believed to be quite low.* Figure 5-23, which shows the estimated gain values, shows a pattern of low (-4 and -7 dBi) gains inbound (5 dBi outbound) similar to the pattern shown for Run 21. Aircraft separation at the point at which tracking was lost on the outbound leg was 3.0 nmi. A single target declaration can be seen at 4.7 nmi outbound.

*This belief is based upon model studies made for a Piper Cherokee Arrow which is a low-wing retractable landing gear aircraft somewhat similar to the Beechcraft Bonanza. See comments made on p. 14 of Ref. 17.

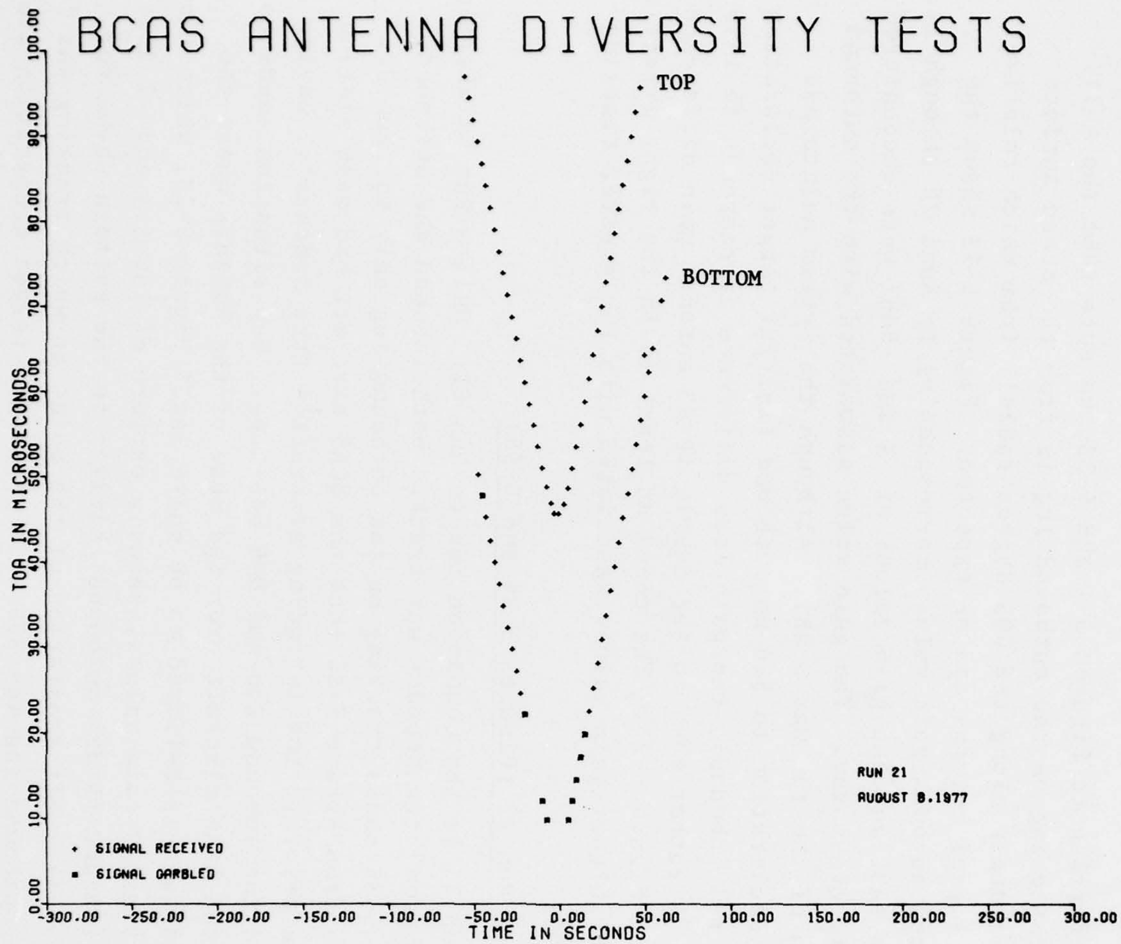


FIGURE 5-32. RUN 21, TOA VALUES

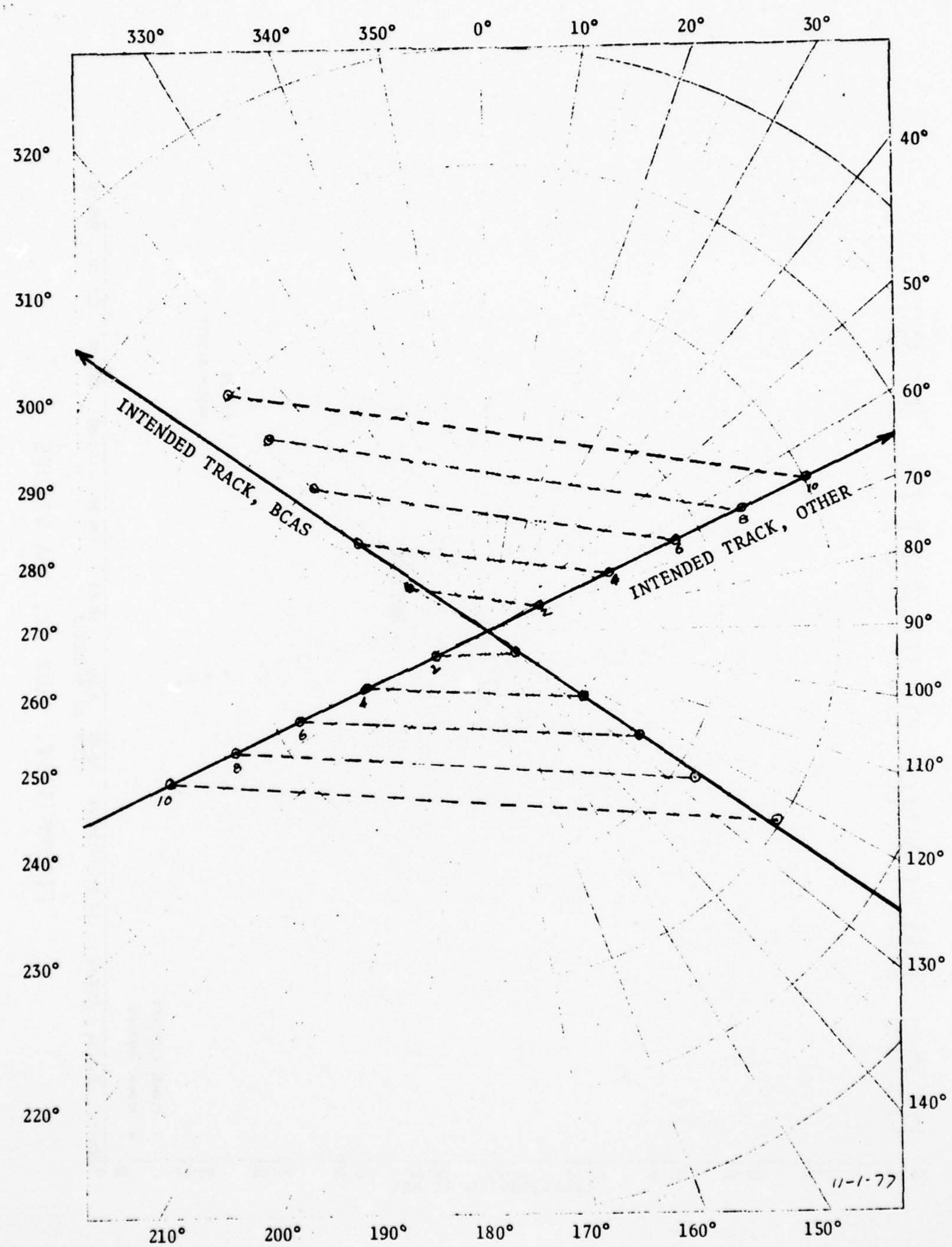


FIGURE 5-33. HORIZONTAL POSITIONS OF AIRCRAFT, RUN 21, WATERLOO VORTAC

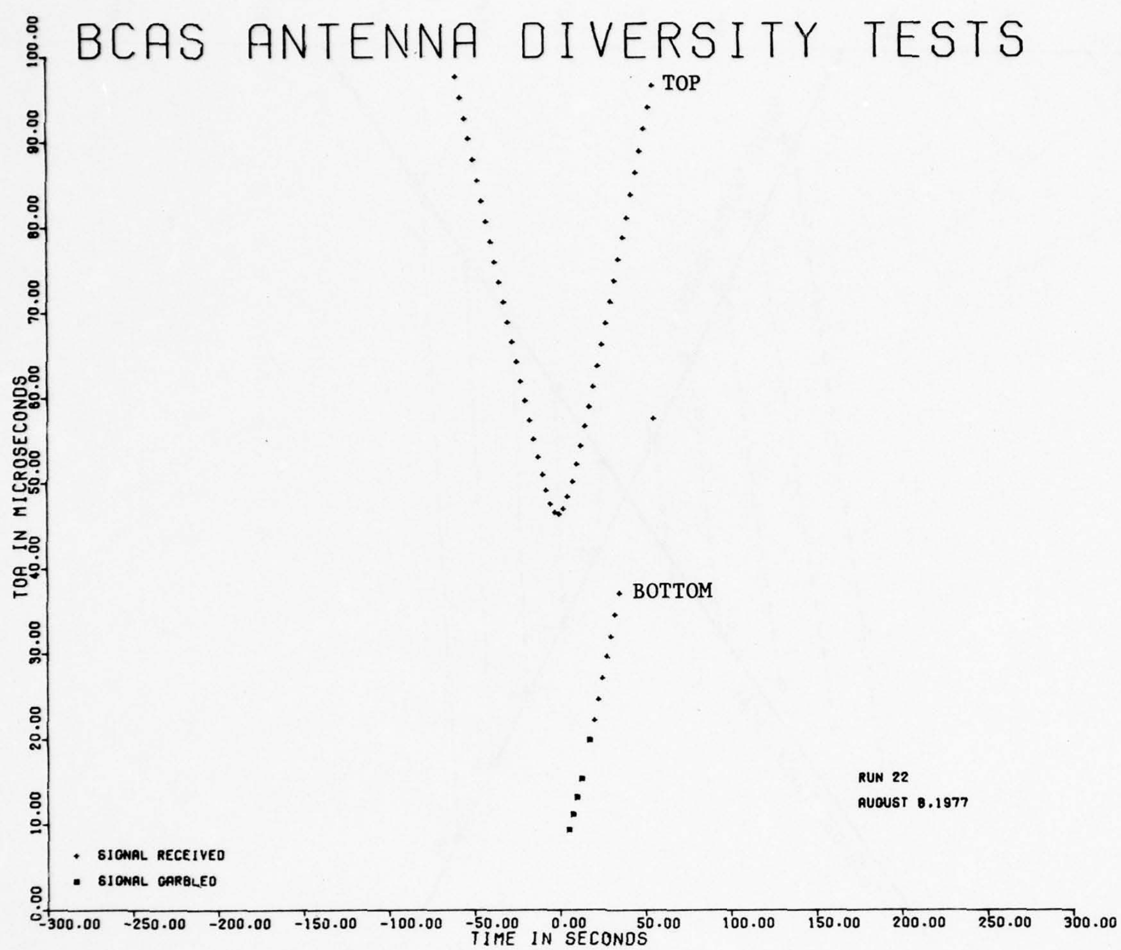


FIGURE 5-34. RUN 22, TOA VALUES

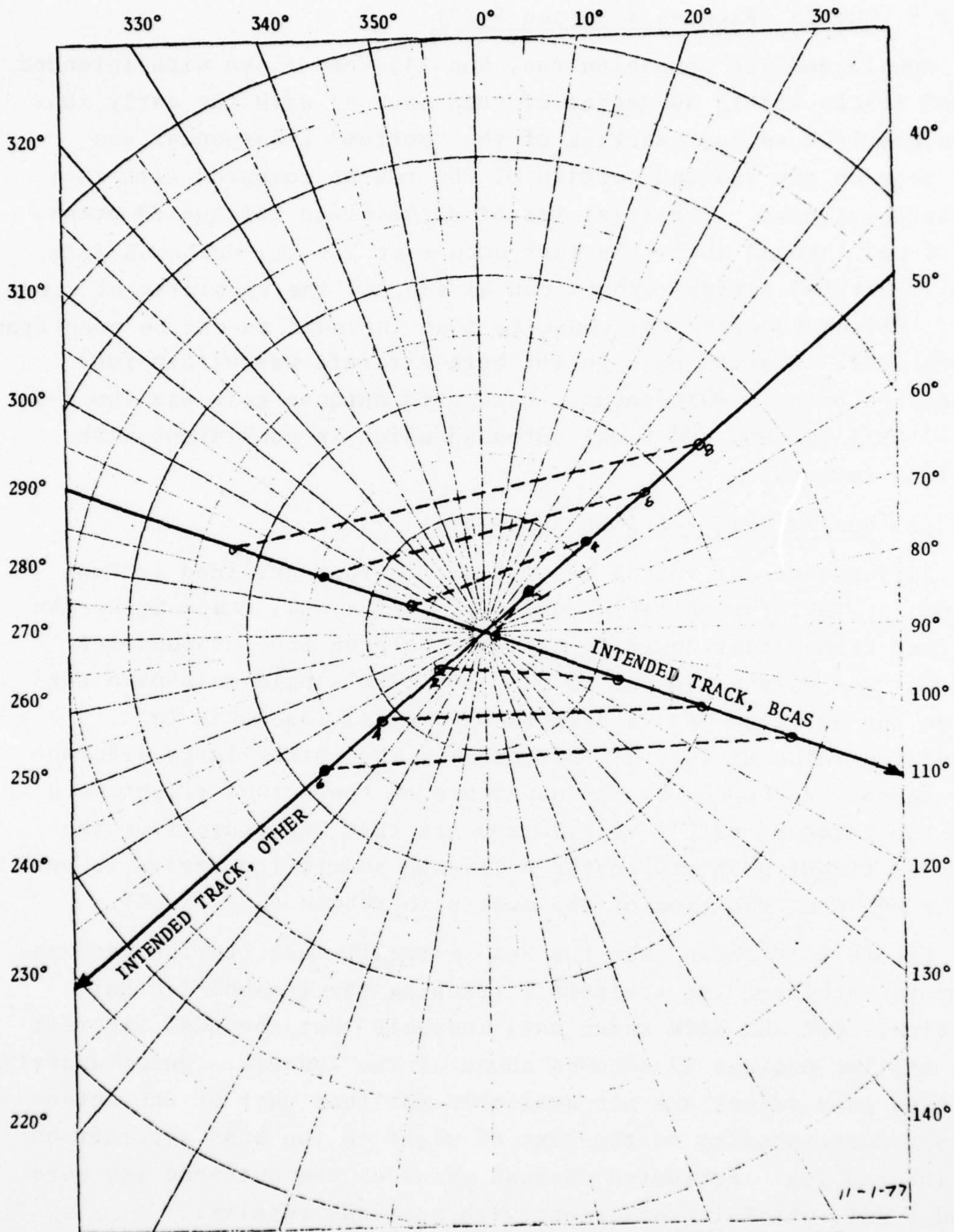


FIGURE 5-35. HORIZONTAL POSITIONS OF AIRCRAFT, RUN 22, WATERLOO VORTAC

5.2.2.8 Run 23 (Figures 5-36 and 5-37)

Run 23 and its companion run, Run 24, were flown with intended ground tracks within 30 degree of head on. As with the early runs flown nearly head on, tracking of the "bottom" transponder was very poor on the inbound portion of the run as compared with that obtained outbound. The first target declaration for Run 23 occurs at 2.0 nmi inbound while the last occurs at 5.9 nmi outbound (Fig. 5-36). Garbled target reports can be seen in the vincinity of cross-over. Flight geometry was close to that intended as can be seen from Figure 5-37. Station passage for both aircraft was within four seconds of being simultaneous. Estimated antenna gain was low (-5 and -7 dBi) inbound and 5 dBi outbound which is consistent with previous results.

5.2.2.9 Run 24 (Figures 5-38 and 5-39)

Performance for Run 24 was similar to that obtained in Runs 22 and 23. But for an isolated target at 5.5 nmi, tracking of the "bottom" transponder could be achieved only on the outbound leg where it was maintained out to 6.3 nmi. The single multipath target on the outbound leg is delayed by 7.81 microseconds (a calculated value of 10.2 microseconds). The rather large discrepancy appears to be due to the departure of the actual flight path from the intended path. It also appears that departure from the intended flight path caused the multipath scattering region to be on the ocean at the time of the multipath return (Fig. 5-38).

Figure 5-39 shows that the BCAS aircraft made station passage prior to the intruding aircraft's reaching the inbound 2.0-nmi position. DME and EAIR radar data indicate that the BCAS aircraft made station passage 52 seconds ahead of the Bonanza. Unfortunately, measured gain values are not available for that part of the antenna pattern corresponding to the line of sight to the BCAS aircraft on the inbound leg. Estimated antenna gains on the outbound leg were 3 and 5 dBi, which is consistent with previous results.

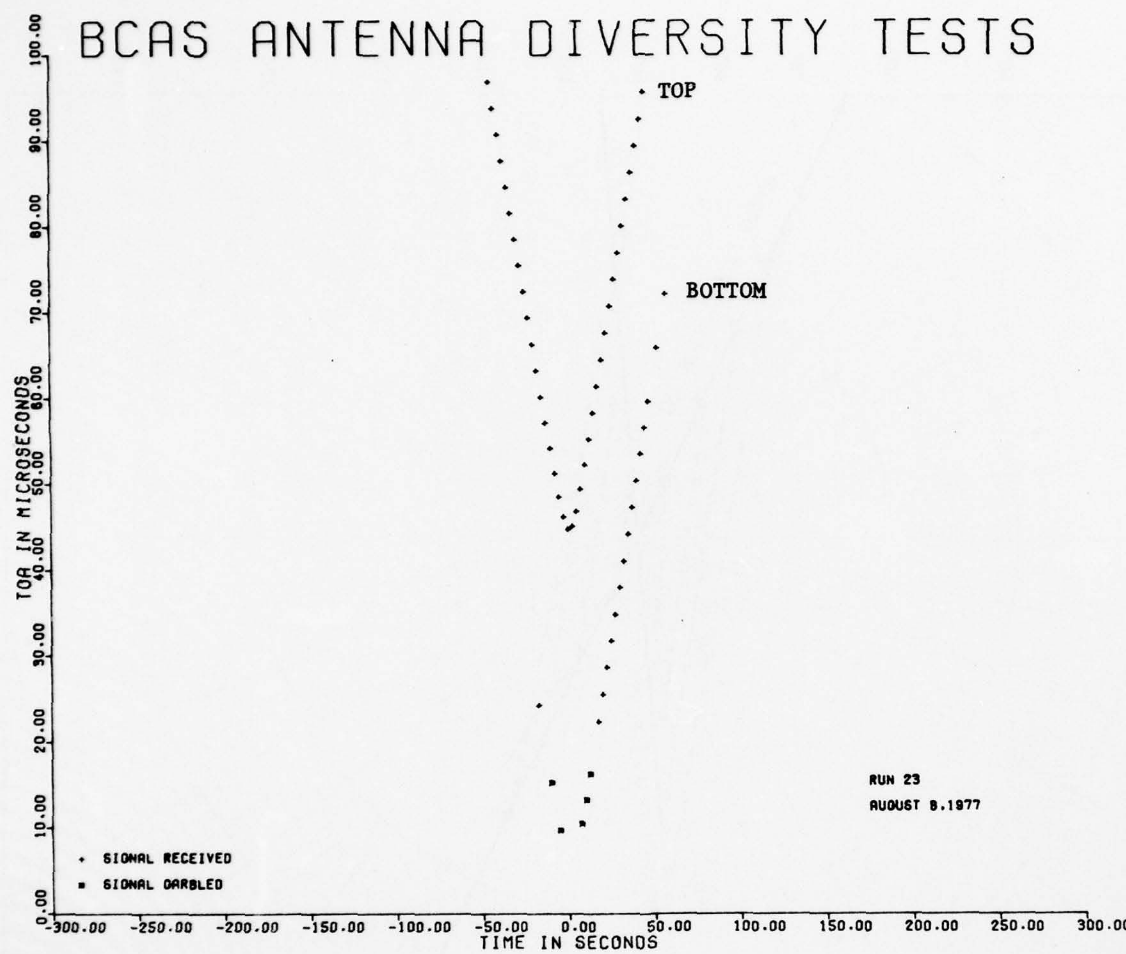


FIGURE 5-36. RUN 23, TOA VALUES

AD-A054 976 TRANSPORTATION SYSTEMS CENTER CAMBRIDGE MASS F/G 17/7
BEACON COLLISION AVOIDANCE SYSTEM (BCAS) AIRBORNE ANTENNA DIVER--ETC(U)
APR 78 J H KRAEMER
UNCLASSIFIED TSC-FAA-78-3 FAA/RD-78/2 NL

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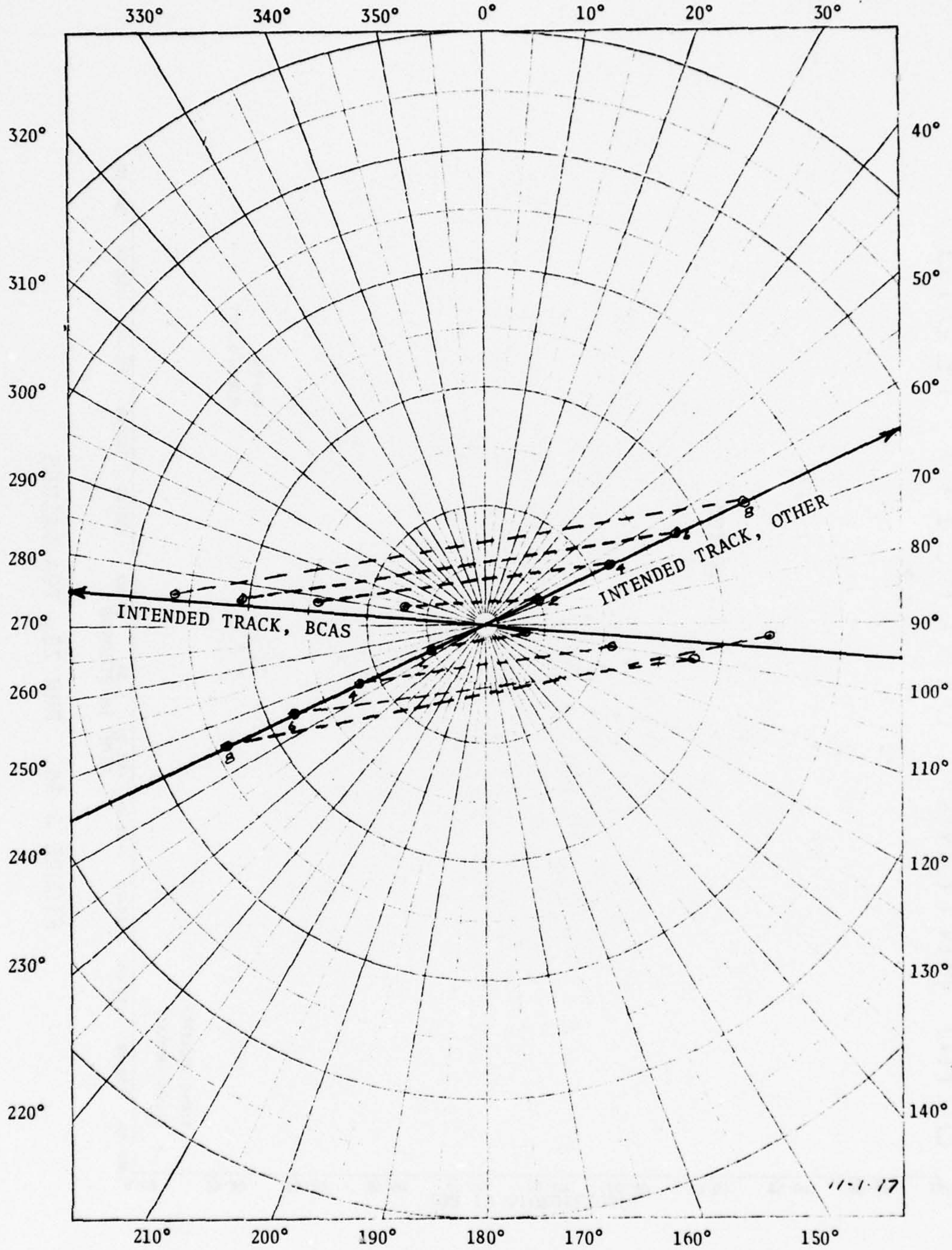


FIGURE 5-37. HORIZONTAL POSITIONS OF AIRCRAFT, RUN 23, WATERLOO VORTAC

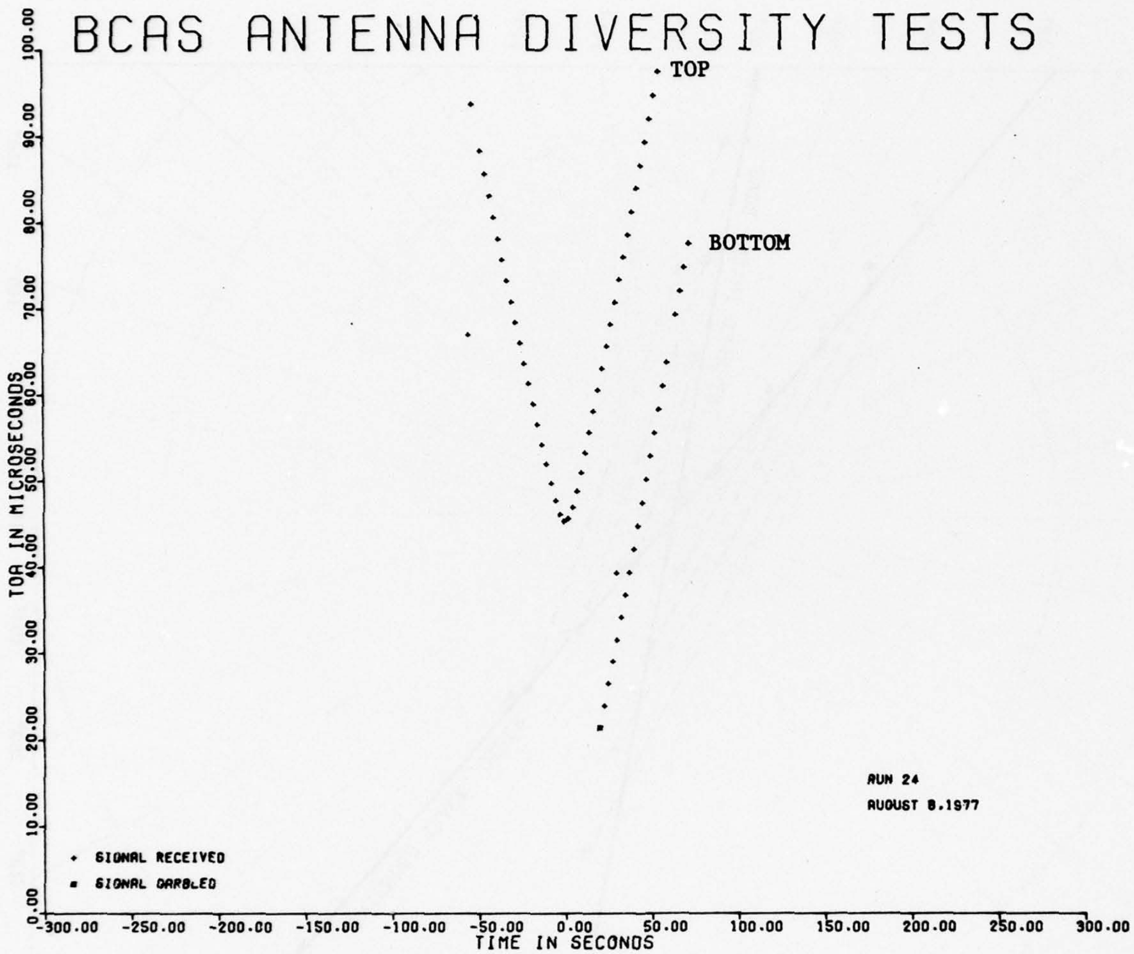


FIGURE 5-38. RUN 24, TOA VALUES

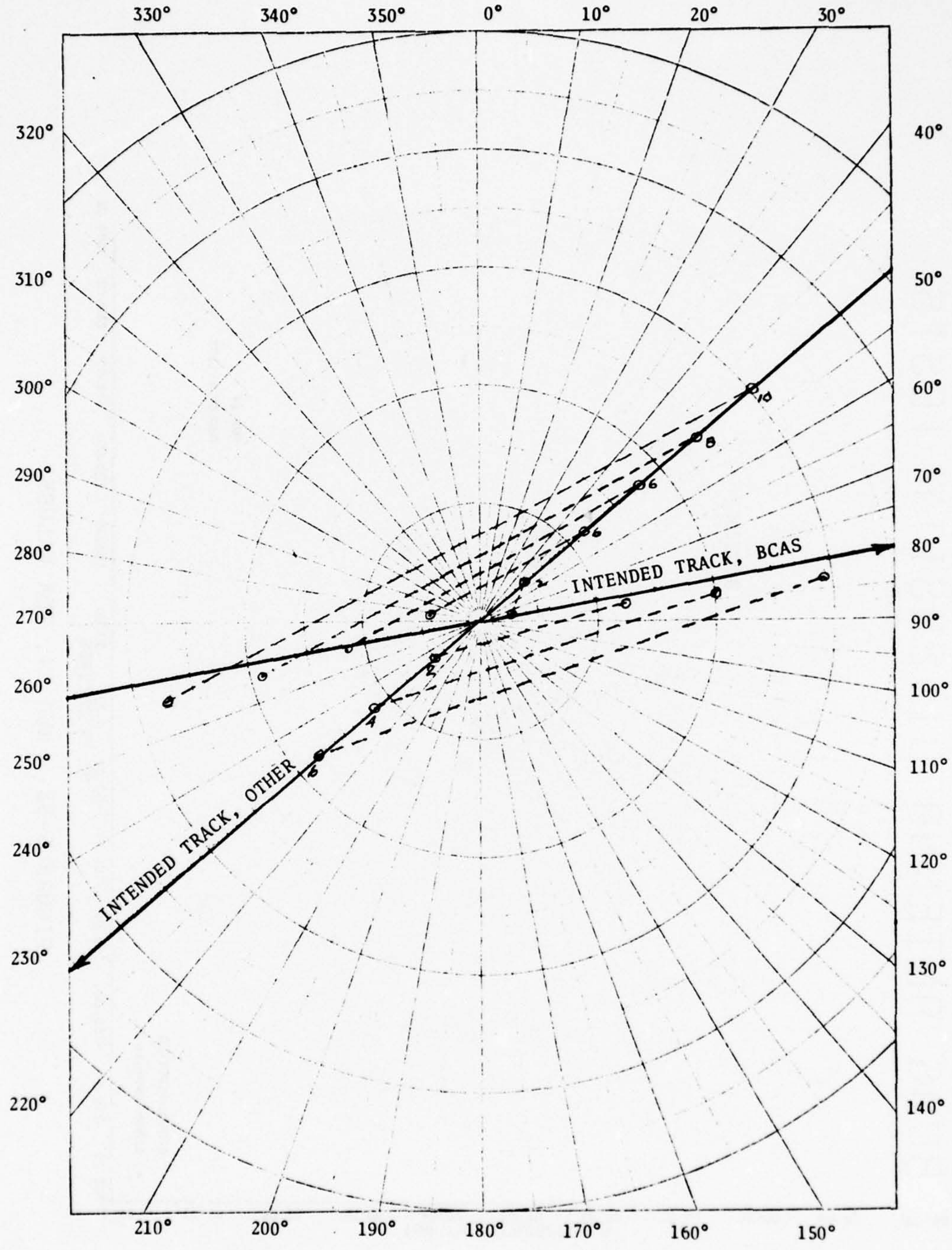


FIGURE 5-39. HORIZONTAL POSITIONS OF AIRCRAFT, RUN 24, WATERLOO VORTAC

5.2.3 Single Antenna Tests, Millville VORTAC

Figure 5-40 shows the time interval over which data were obtained on each of the 24 runs which make up the daisy pattern. The cross-hatched region indicates the presence of data associated with the active mode of interrogation by the BCAS aircraft. The solid region indicates the presence of target data associated with replies elicited by the ASR-5 radar. Runs may be thought of as being grouped in pairs (i.e., Runs 1 and 2, 3 and 4, etc.) which have the same intended flight geometry. Runs 1 and 2 are head-on approaches; Runs 3 and 4 have intended ground tracks which intersect at 30 degree, etc. The relative bearing of the intruding aircraft with respect to the BCAS aircraft is indicated by the angle ϕ. Zero degrees is taken as being directly ahead with positive values increasing in a clockwise direction toward the right wing. Figure 5-40 indicates only the presence or absence of target report data and does not indicate data quality. No data are shown for Run 2 since it contained only two target reports for the BCAS interrogator and a single target report for the ASR-5. No data were collected on Runs 10 and 11 due to problems associated with loading of the BCAS software into the system. Similarly, most of Run 22 and all of Run 23 were lost due to an apparent software difficulty which required that the program be reloaded.

Data for the single antenna tests are presented in groups of three plots for each run. The first plot in each group is derived from the active mode, and shows TOA values associated with replies elicited by the on-board BCAS interrogator. The second and third plots in each group are derived from the passive mode, and show TOA and DAZ values associated with replies elicited by the ASR-5 radar. An indication of ASR-5 radar lock is provided on each plot to show whether or not the BCAS system was locked to the ASR-5. This information is essential to the proper interpretation of the data presented since radar lock is necessary for target declaration in the passive mode. Both types of data (active and passive mode) were gathered simultaneously since the BCAS system was operated in the I-33 mode with a single locked SSR (the ASR-5). The

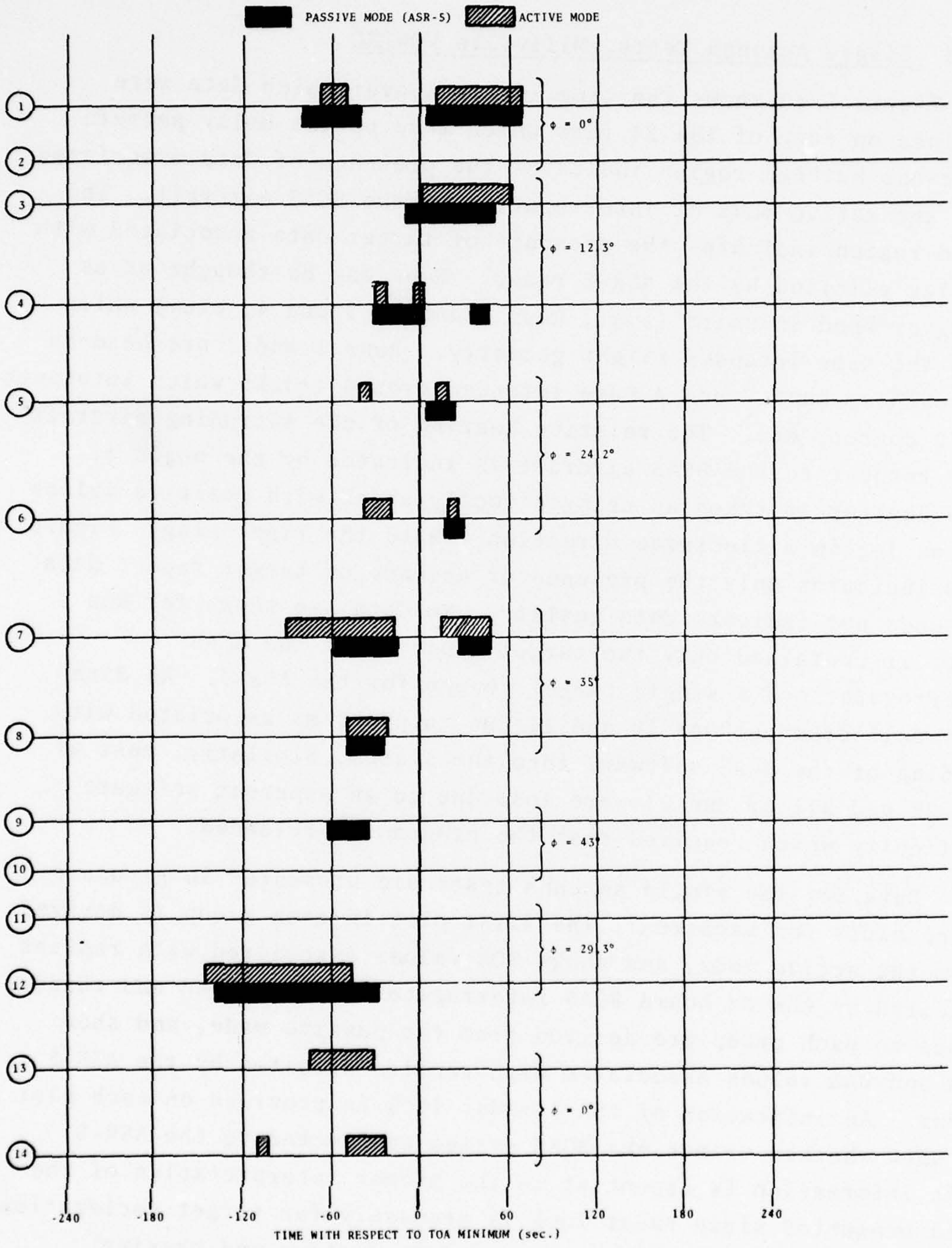
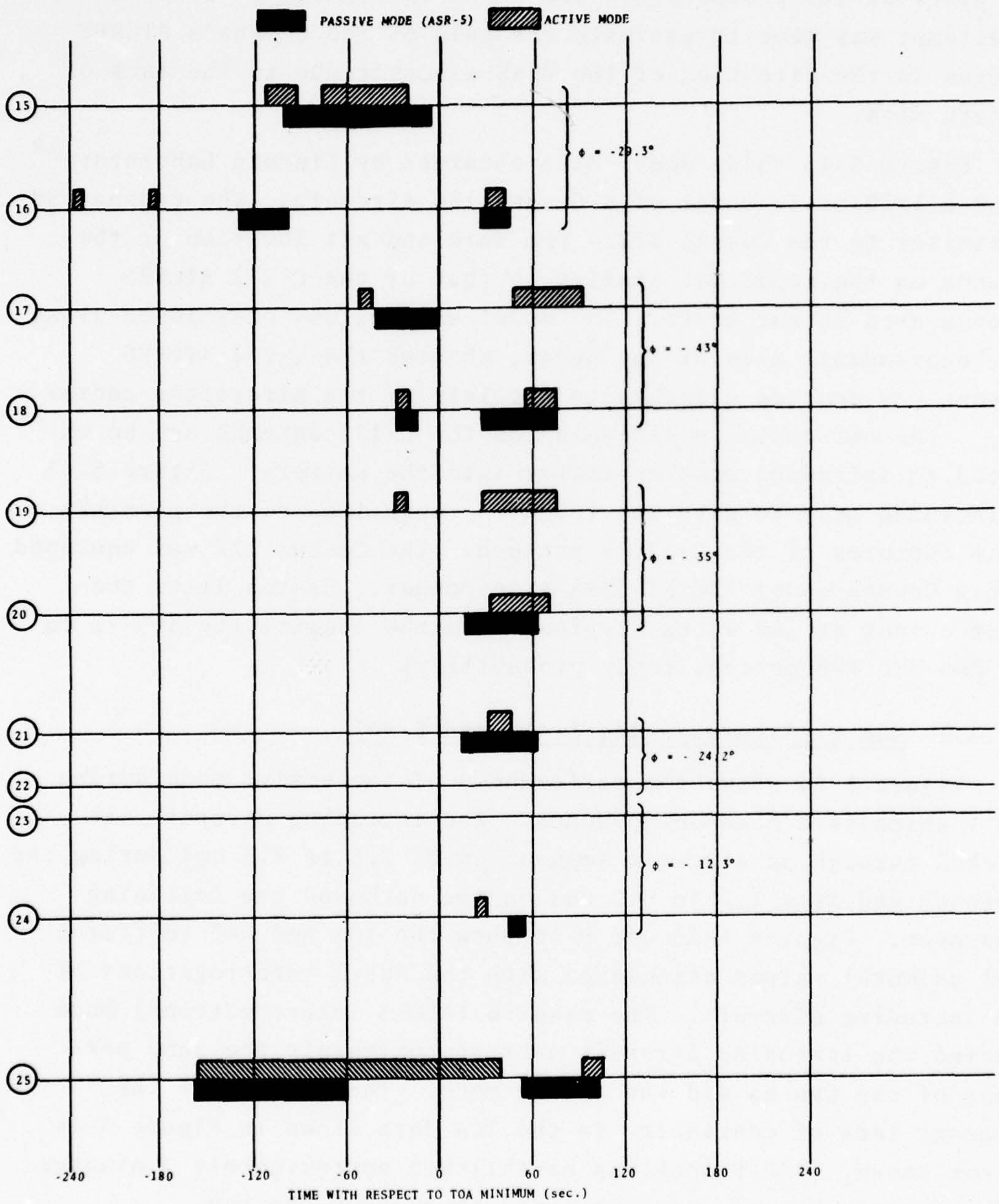


FIGURE 5-40. REGIONS OF TARGET DECLARATION-
SINGLE ANTENNA TESTS, MILLVILLE VORTAC



*Note: Run 25 is not a part of the daisy over figure-eight pattern.

FIGURE 5-40. REGIONS OF TARGET DECLARATION-SINGLE ANTENNA TESTS, MILLVILLE VORTAC (CONTINUED)

intruding aircraft (the Cessna 172) was tracked by the EAIR Radar, and plots of its ground track are shown in Figures 5-41 and 5-42. No attempt was made to estimate the gain of the Cessna's ATCRBS antenna in the direction of the BCAS aircraft due to the lack of pattern data.

Figure 5-43 shows model data obtained by Lincoln Laboratory[18] using a 1/20-scale model of a Cessna 150 aircraft. The Cessna 150 is similar to the Cessna 172. The fore-and-aft location of the antenna on the model was similar to that of the C-172 ATCRBS antenna used in our tests. The model antenna was positioned along the longitudinal axis of the model, whereas the C-172 ATCRBS antenna was mounted 6 inches to the left of the aircraft's center line. The off-center positioning of the C-172 antenna can be expected to introduce some asymmetry into the pattern. Figure 5-43 is included only to give the reader a rough idea of the possible gross features of the C-172's pattern. The Cessna 172 was equipped with a Cessna model ARC RT-359A transponder. Cessna lists the power output at 125 watts "typical" and the sensitivity as -72 to -80 dBm MTL (90 percent reply probability).

5.2.3.1 Run 1 (Figures 5-44, 5-45, and 5-46)

Figure 5-44 shows the performance of the active mode during Run 1 which is a head-on approach. The intruding aircraft was tracked through an aircraft separation of 2.6 to 2.3 nmi during the approach and from 1.7 to 6.2 nmi on the outbound leg following crossover. Figures 5-45 and 5-46 show the TOA and DAZ (differential azimuth) values associated with the ASR-5 interrogations of the intruding aircraft. The passive (ASR-5 interrogations) mode tracked the intruding aircraft over approximately the same portions of the run as did the active mode. The reason for the apparent lack of continuity in the TOA data shown in Figure 5-44 is not known. ASR-5 lock was established approximately 3 minutes before crossover and was maintained throughout the run.

5.2.3.2 Run 2

No plots are shown for Run 2 inasmuch as only three target declarations were made during this run.

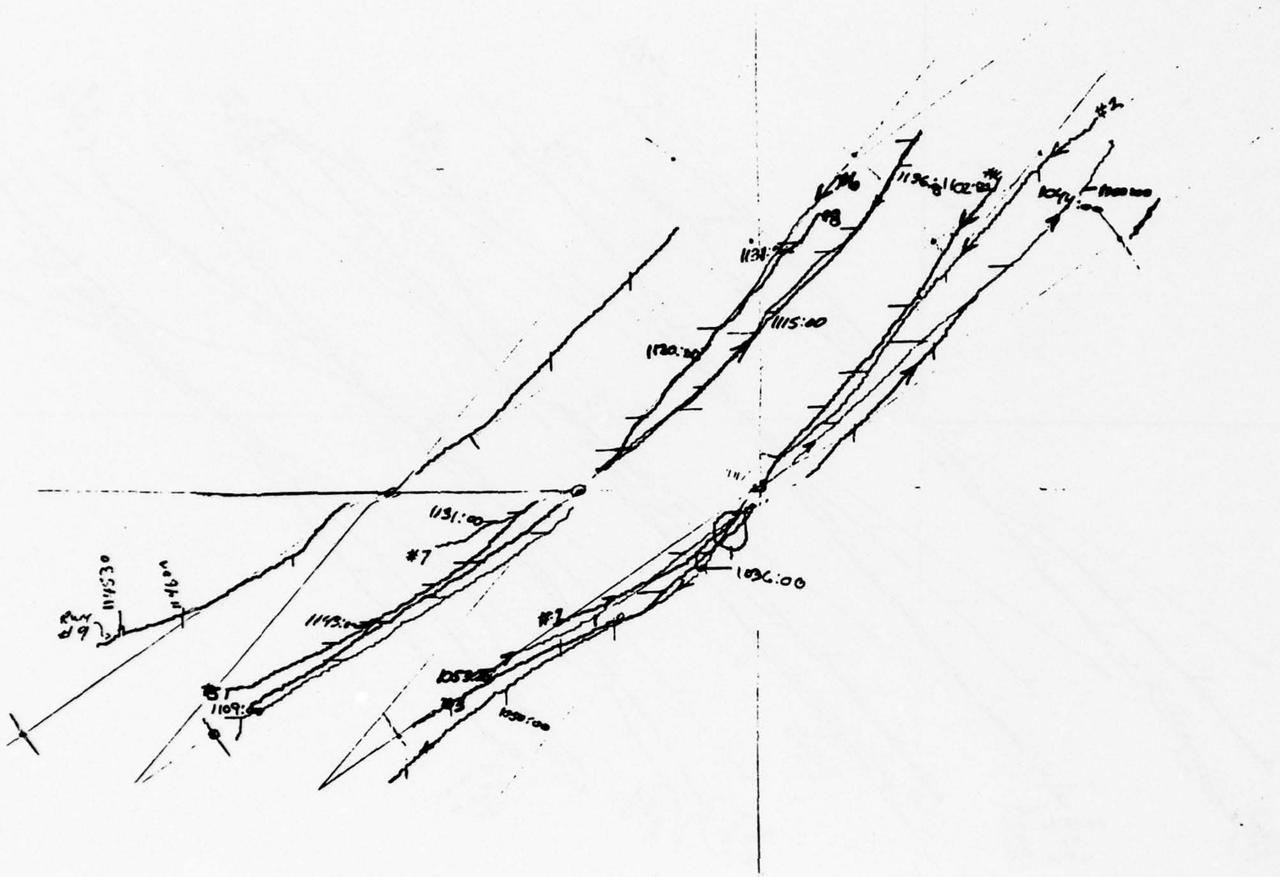


FIGURE 5-41. EAIR PLOT OF CESSNA 172 GROUND TRACKS, RUNS 1-9, MILLVILLE VORTAC

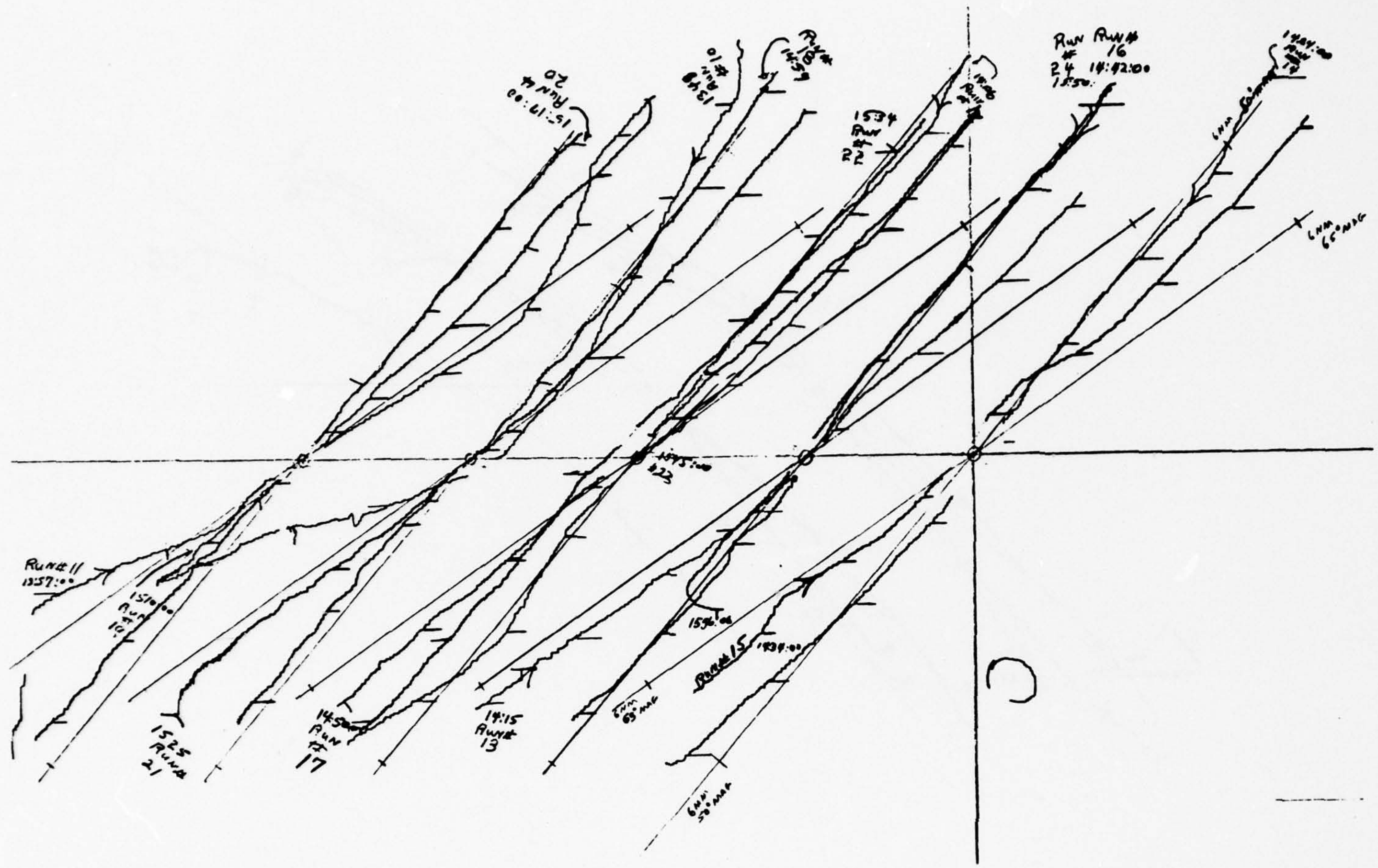


FIGURE 5-42. EAIR PLOT OF CESSNA 172 GROUND TRACKS, RUNS 10-24, MILLVILLE VORTAC

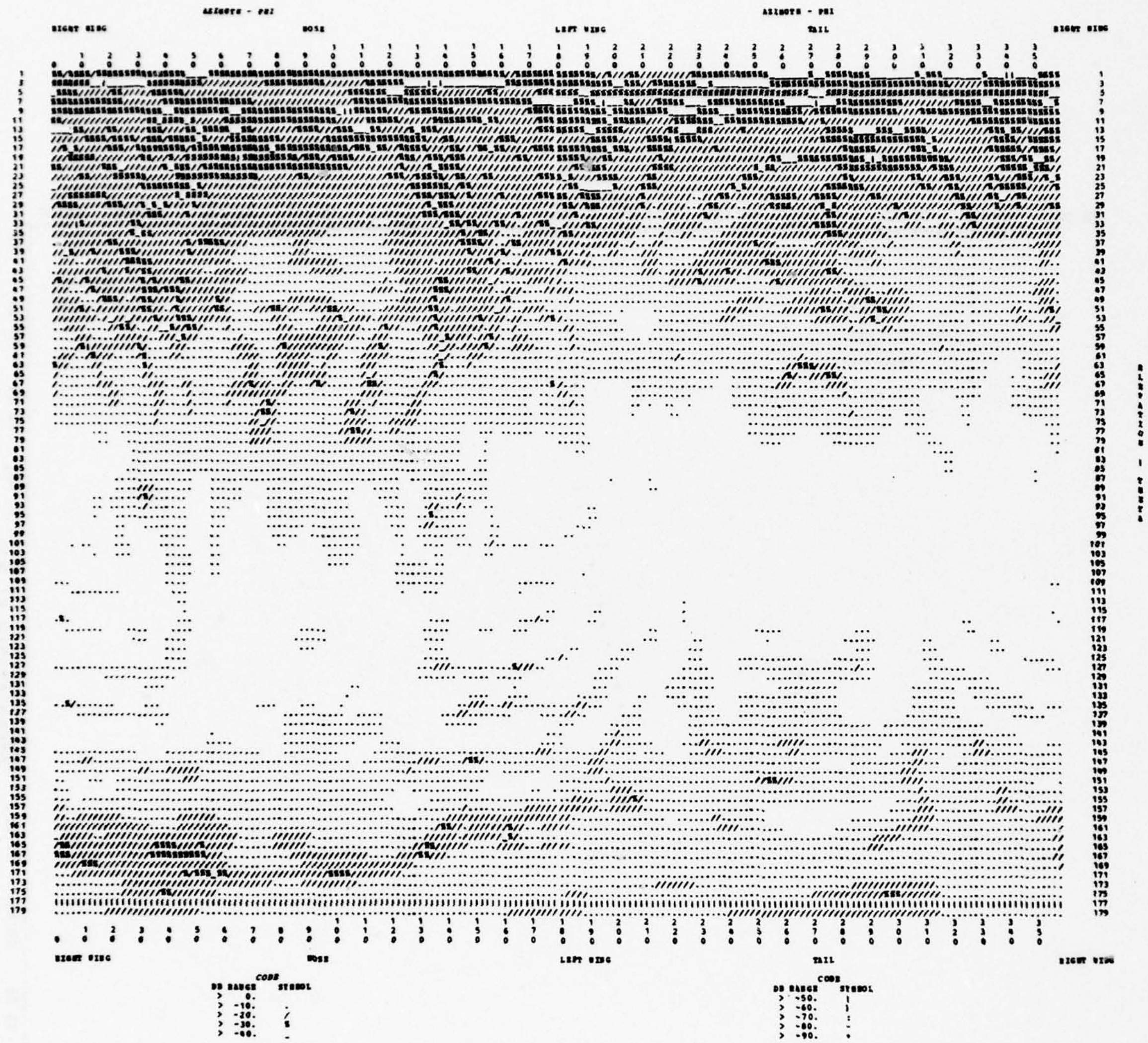


FIGURE 5-43. CESSNA 150 BOTTOM MOUNTED ATCRBS ANTENNA PATTERN (Courtesy: LINCOLN LABORATORY. SCALE-MODEL DATA)

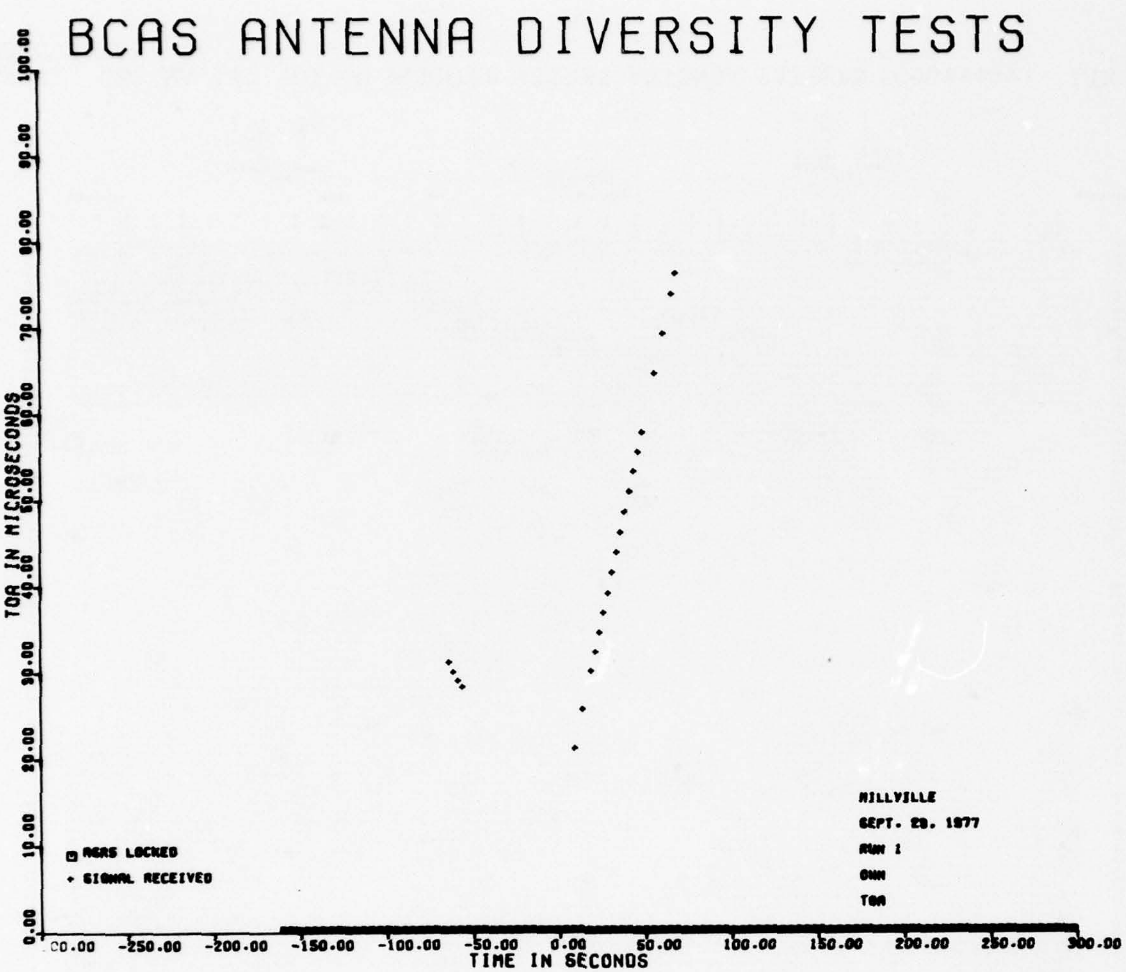


FIGURE 5-44. RUN 1, ACTIVE MODE TOA DATA

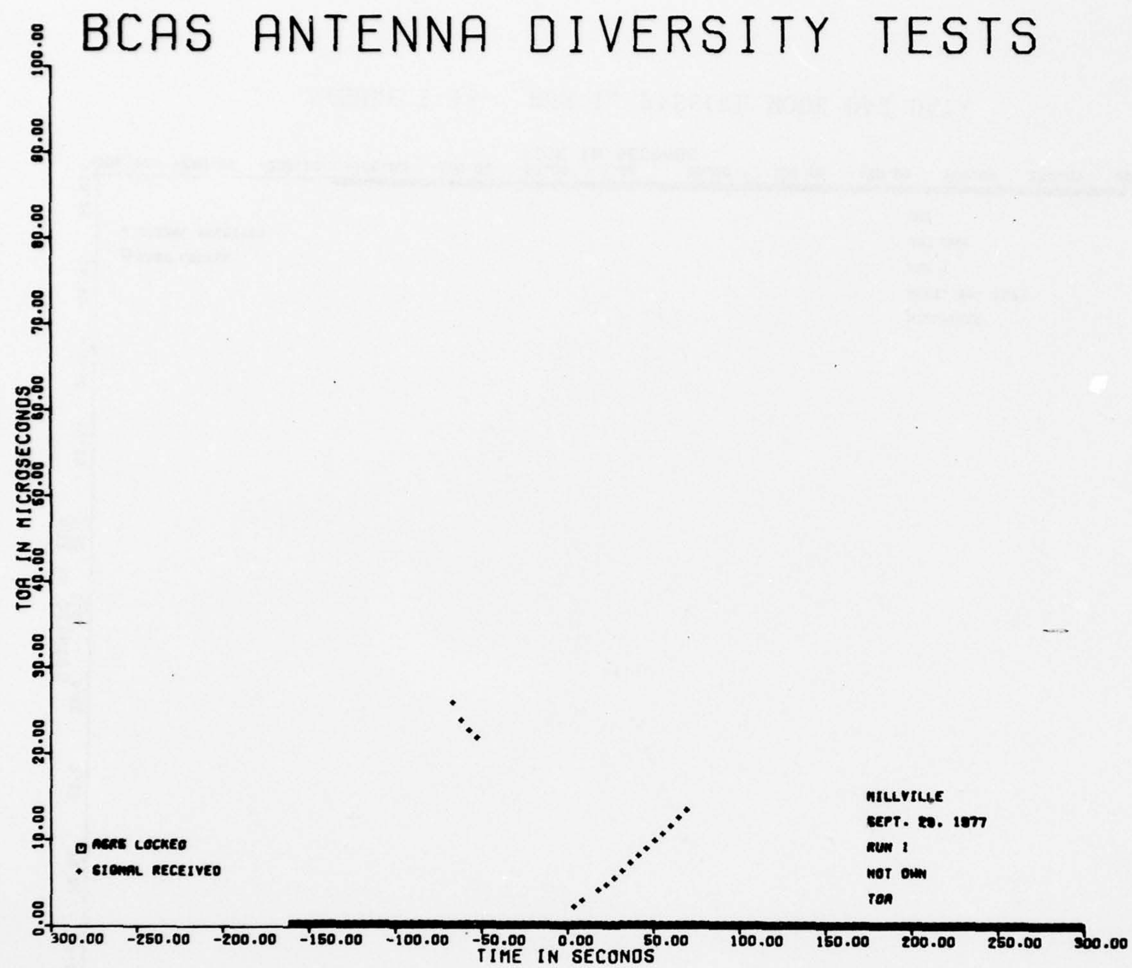


FIGURE 5-45. RUN 1, PASSIVE MODE TOA DATA

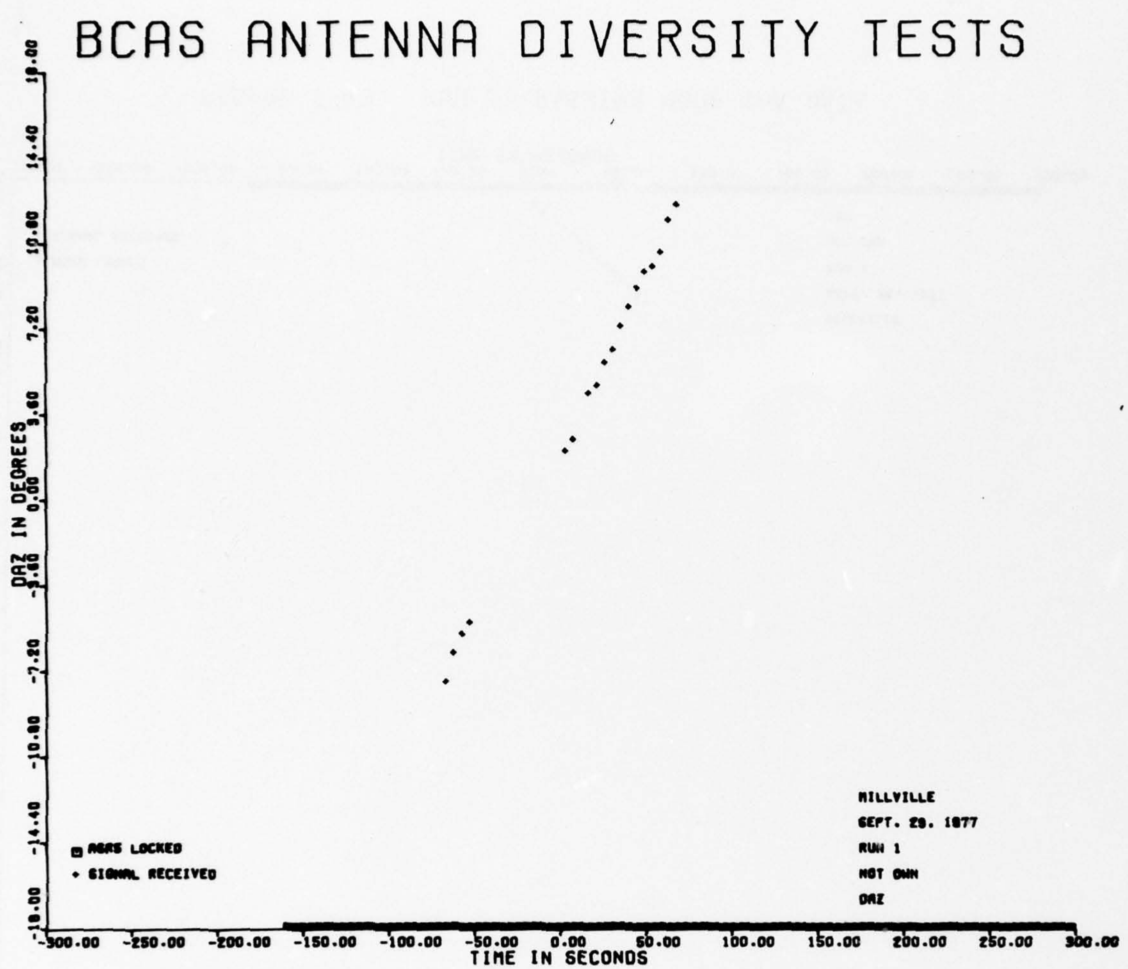


FIGURE 5-46. RUN 1, PASSIVE MODE DAZ DATA

5.2.3.3 Run 3 (Figures 5-47, 5-48, and 5-49)

Figures 5-47 and 5-48 indicate that the intruding aircraft was tracked only on the outbound leg following crossover. As with Run 1, both the active mode (Figure 5-47) and the passive mode (Figures 5-48 and 5-49) tracked the Cessna over approximately the same protion of the run. Aricraft separation at the beginning and end of the data shown in Figure 5-47 was 1.9 and 7.3 nmi, respectively. With the exception of a single scan occurring approximately 2 minutes before crossover, ASR-5 lock was maintained throughout the run.

5.2.3.4 Run 4 (Figures 5-50, 5-51, and 5-52)

Figure 5-50 shown only five target declarations associated with active mode operation. Aircraft separation ranged from 3.7 to 1.9 nmi inbound for the initial and final points plotted in Figure 5-50. The passive mode of operation depicted in Figures 5-51 and 5-52 shows only marginally better performance than in the active mode. ASR-5 lock was maintained throughout the run.

5.2.3.5 Run 5

No data are presented for Run 5. Six target declarations were made in the active mode, and four in the passive mode.

5.2.3.6 Run 6 (Figures 5-53, 5-54, and 5-55)

Figure 5-53 shows only limited data were obtained in the active mode. Inbound tracking (active) extended from 3.1 to 1.9 nmi with only two target declarations on the outbound leg. Only three target declarations were made in the passive mode. ASR-5 lock was lost from approximately 3-1/2 minutes to 1 minute before crossover. See Figures 5-54 and 5-55.

5.2.3.7 Run 7 (Figures 5-56, 5-57, and 5-58)

Figure 5-56 shows the plot of target declarations for the active mode on Run 7. Tracking began at an aircraft separation of 5.5 nmi on the inbound leg and continued, with interruptions, to 1.7 nmi. Outbound tracking provided only five target declarations between 1.8 and 3.3 nmi. Figures 5.57 and 5.58 show the TOA and DAZ values derived from the ASR-5 interrogations. Tracking

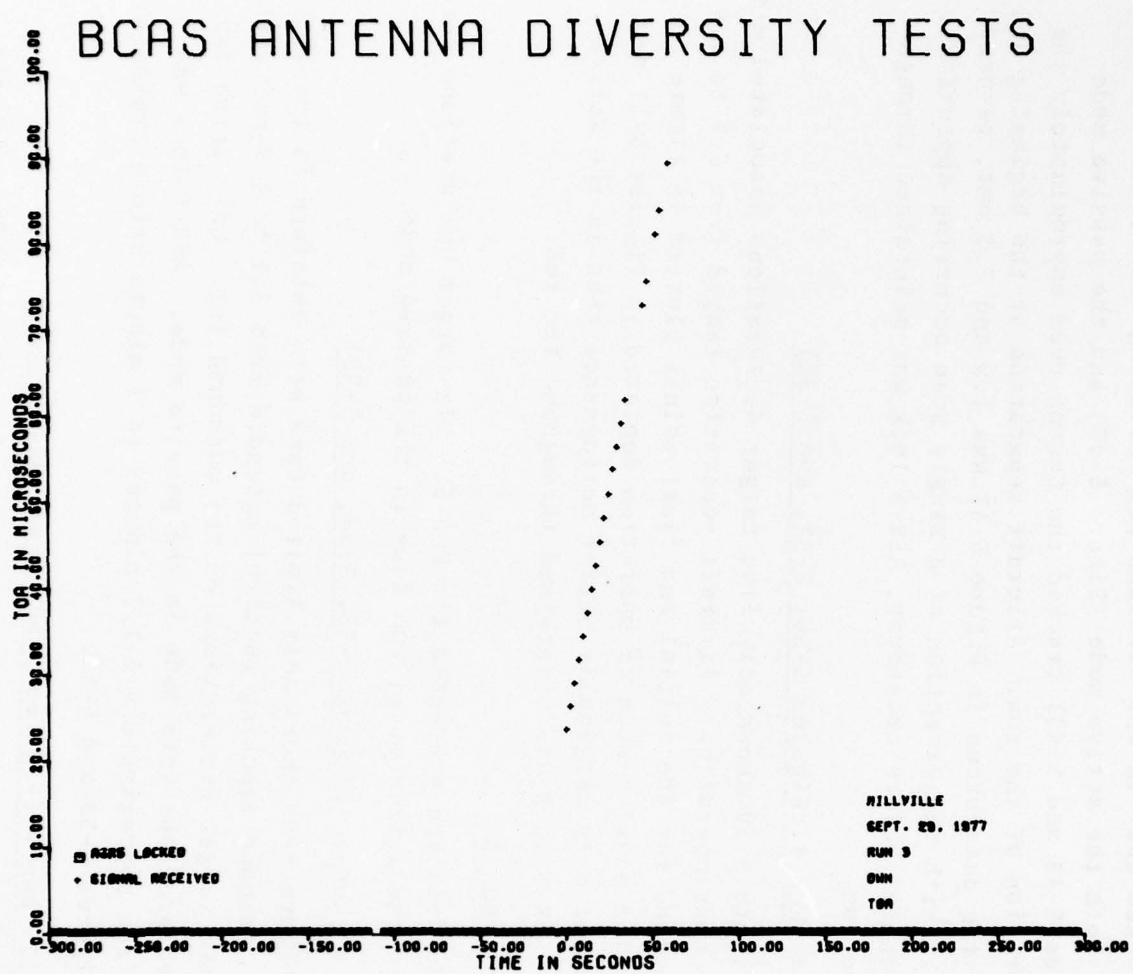


FIGURE 5-47. RUN 3, ACTIVE MODE TOA DATA

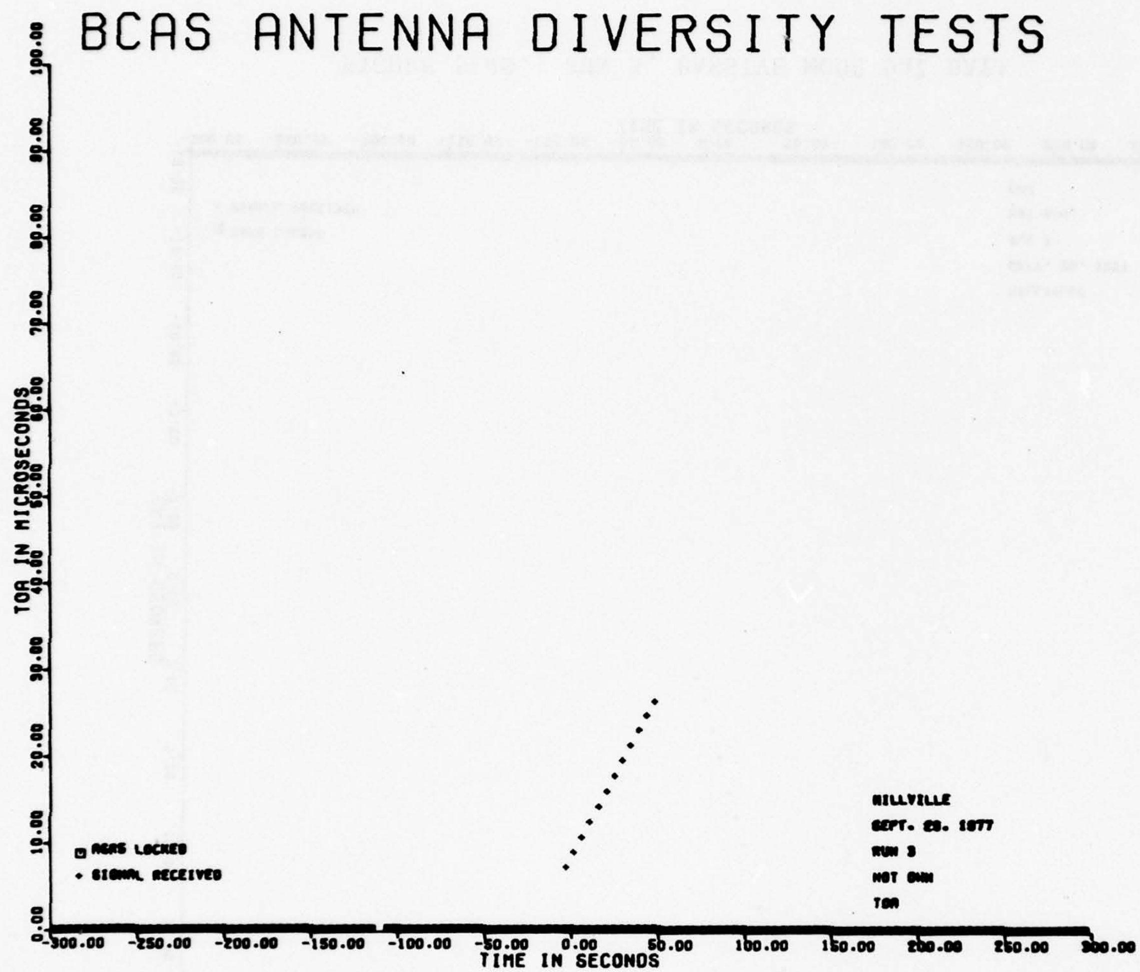


FIGURE 5-48. RUN 3, PASSIVE MODE TOA DATA

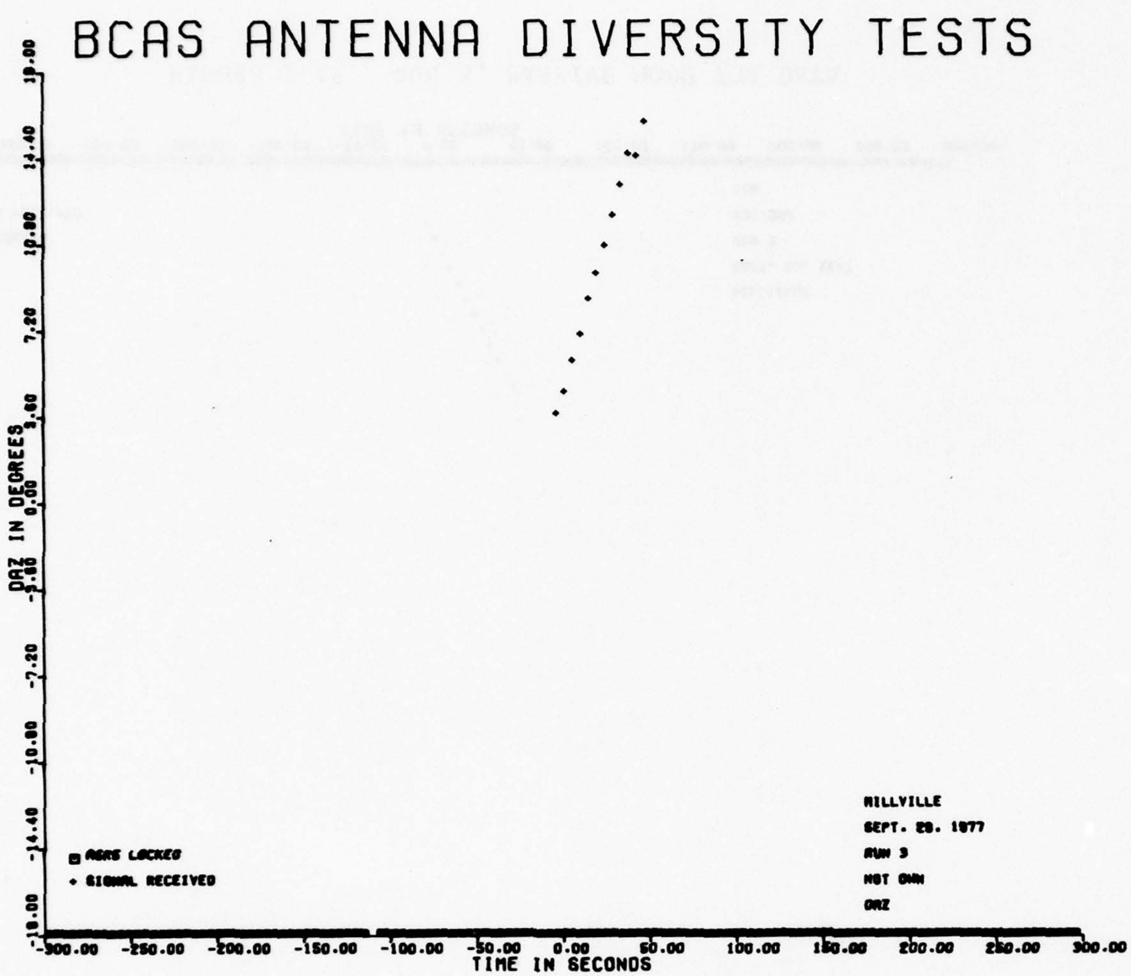


FIGURE 5-49. RUN 3, PASSIVE MODE DAZ DATA

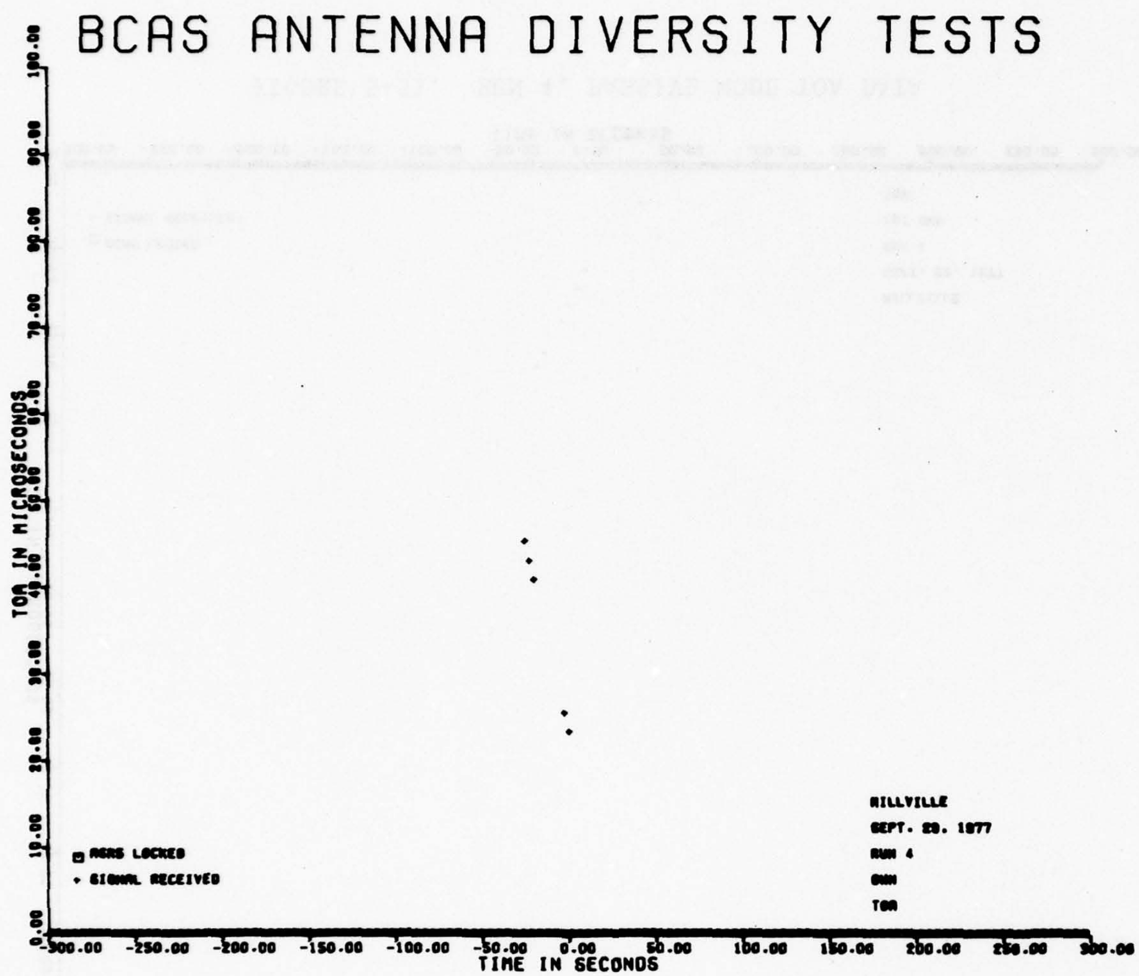


FIGURE 5-50. RUN 4, ACTIVE MODE TOA DATA

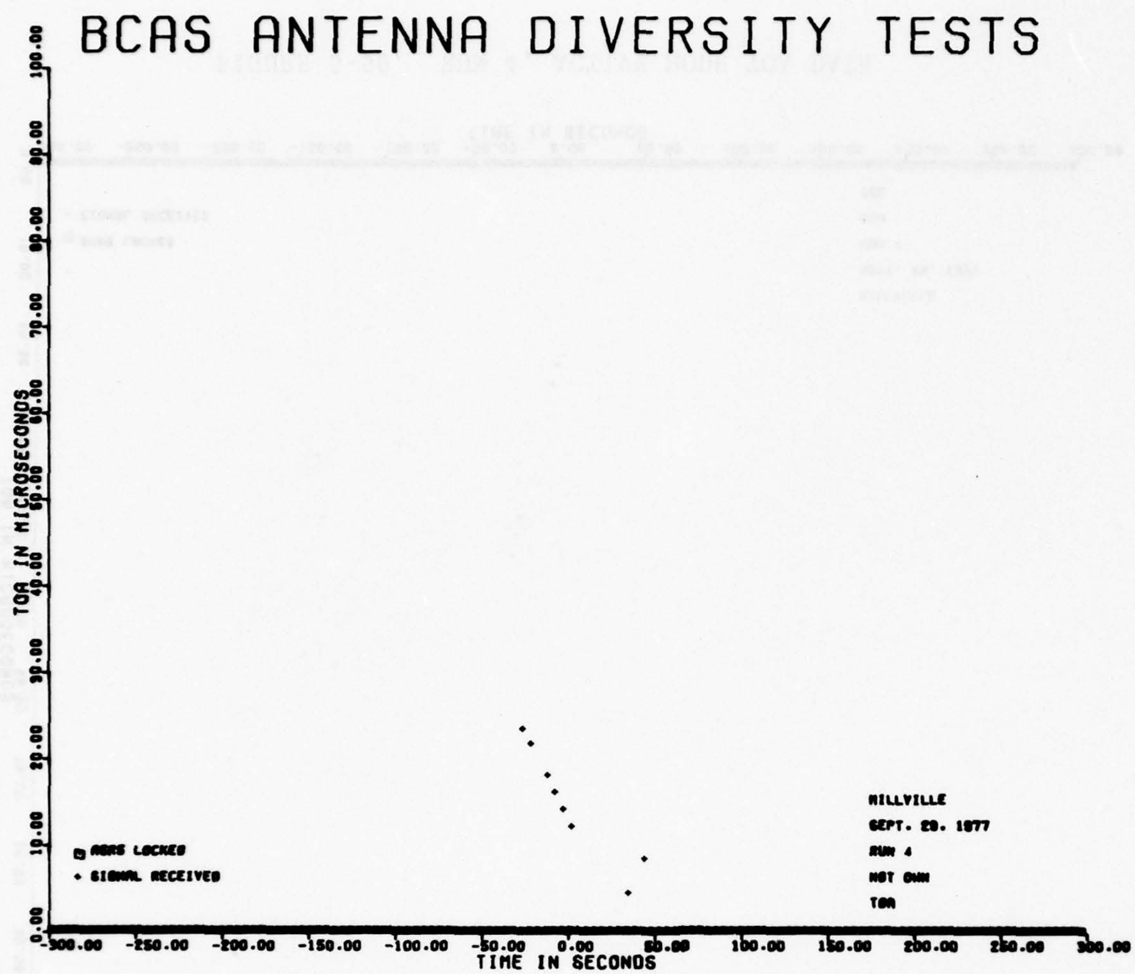


FIGURE 5-51. RUN 4, PASSIVE MODE TOA DATA

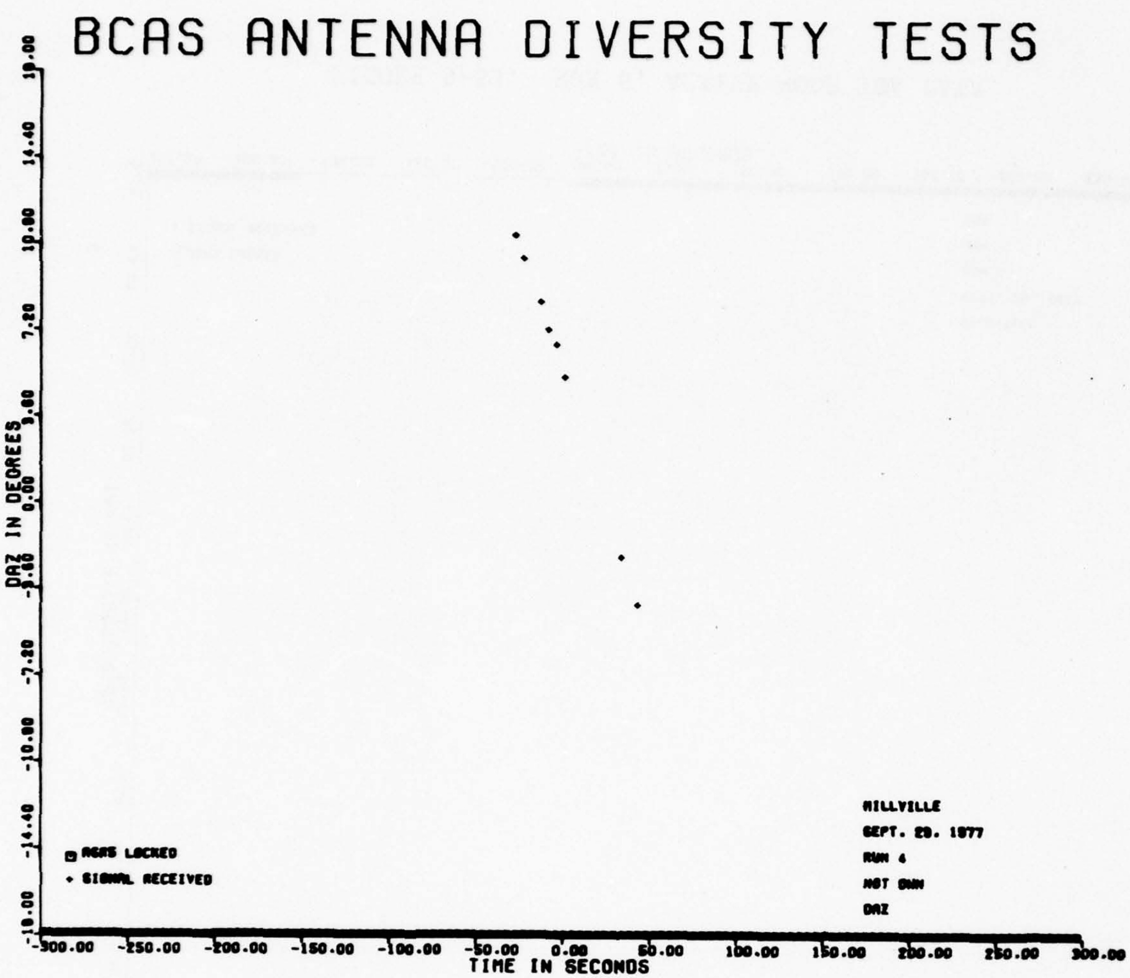


FIGURE 5-52. RUN 4, PASSIVE MODE DAZ DATA

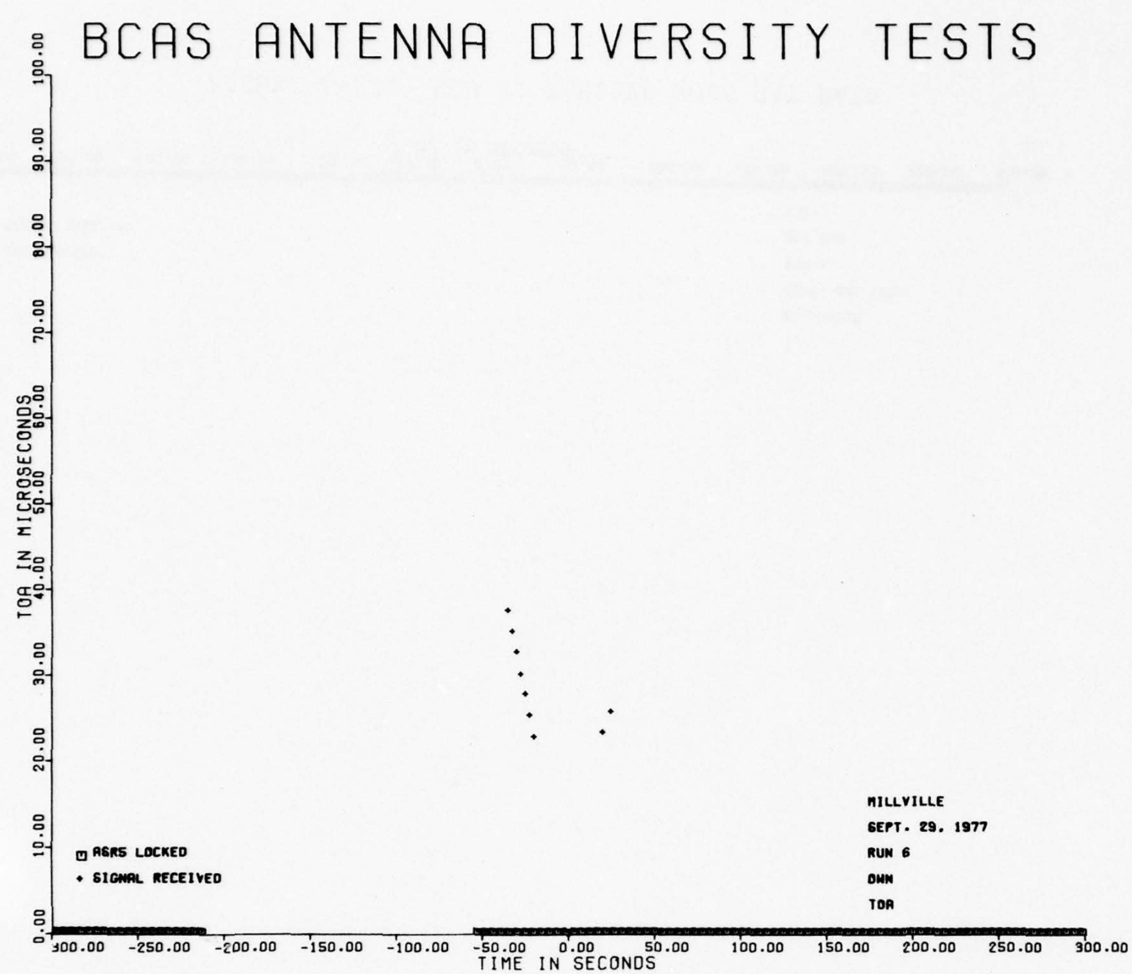


FIGURE 5-53. RUN 6, ACTIVE MODE TOA DATA

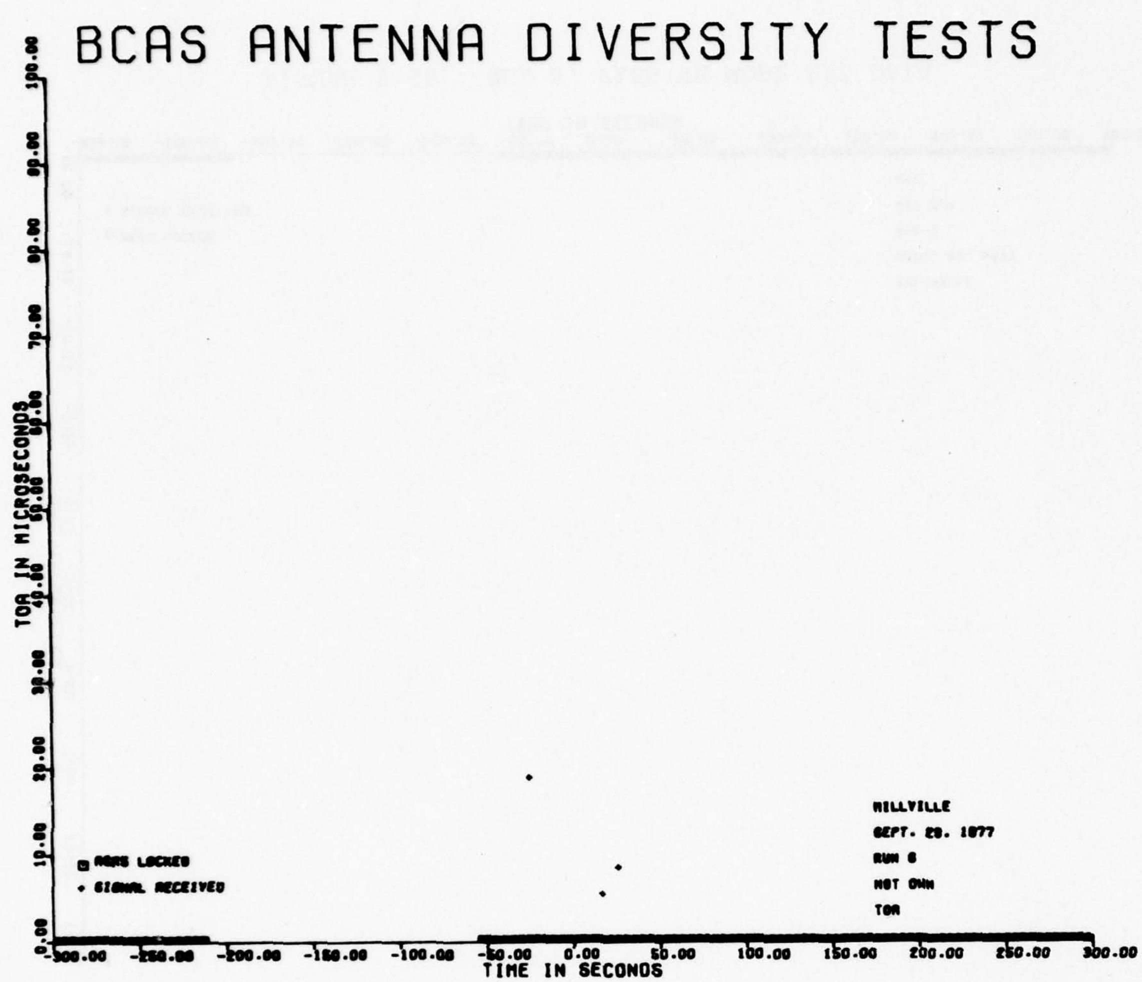


FIGURE 5-54. RUN 6, PASSIVE MODE TOA DATA

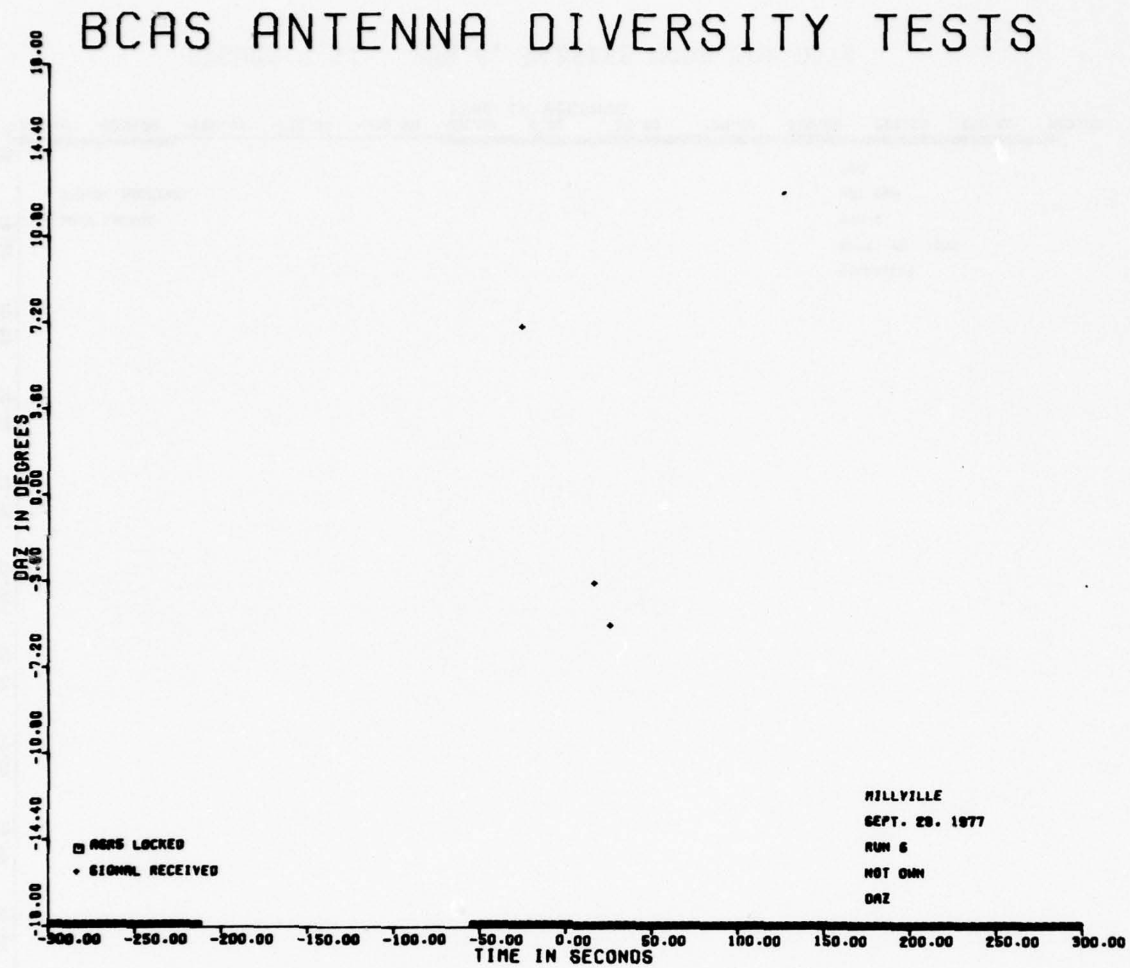


FIGURE 5-55. RUN 6, PASSIVE MODE DAZ DATA

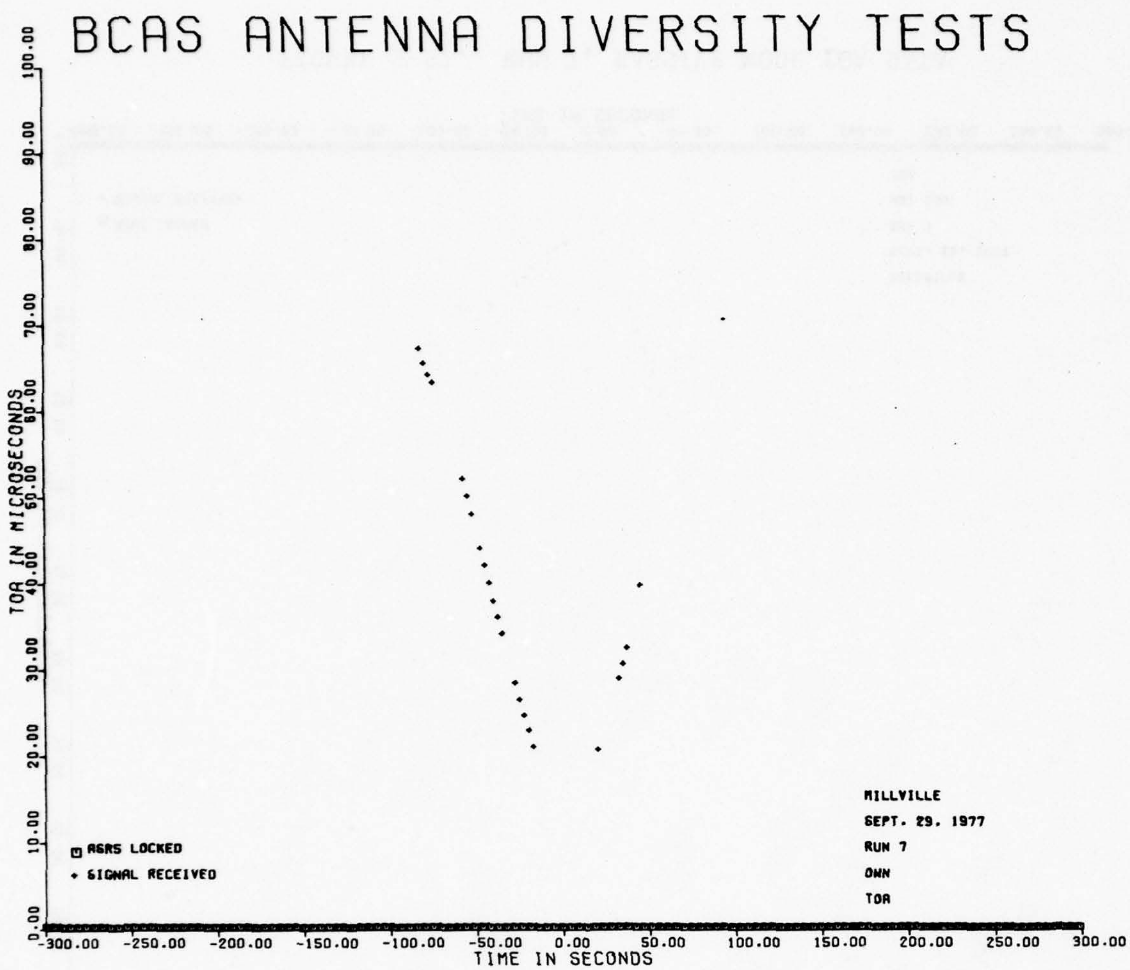


FIGURE 5-56. RUN 7, ACTIVE MODE TOA DATA

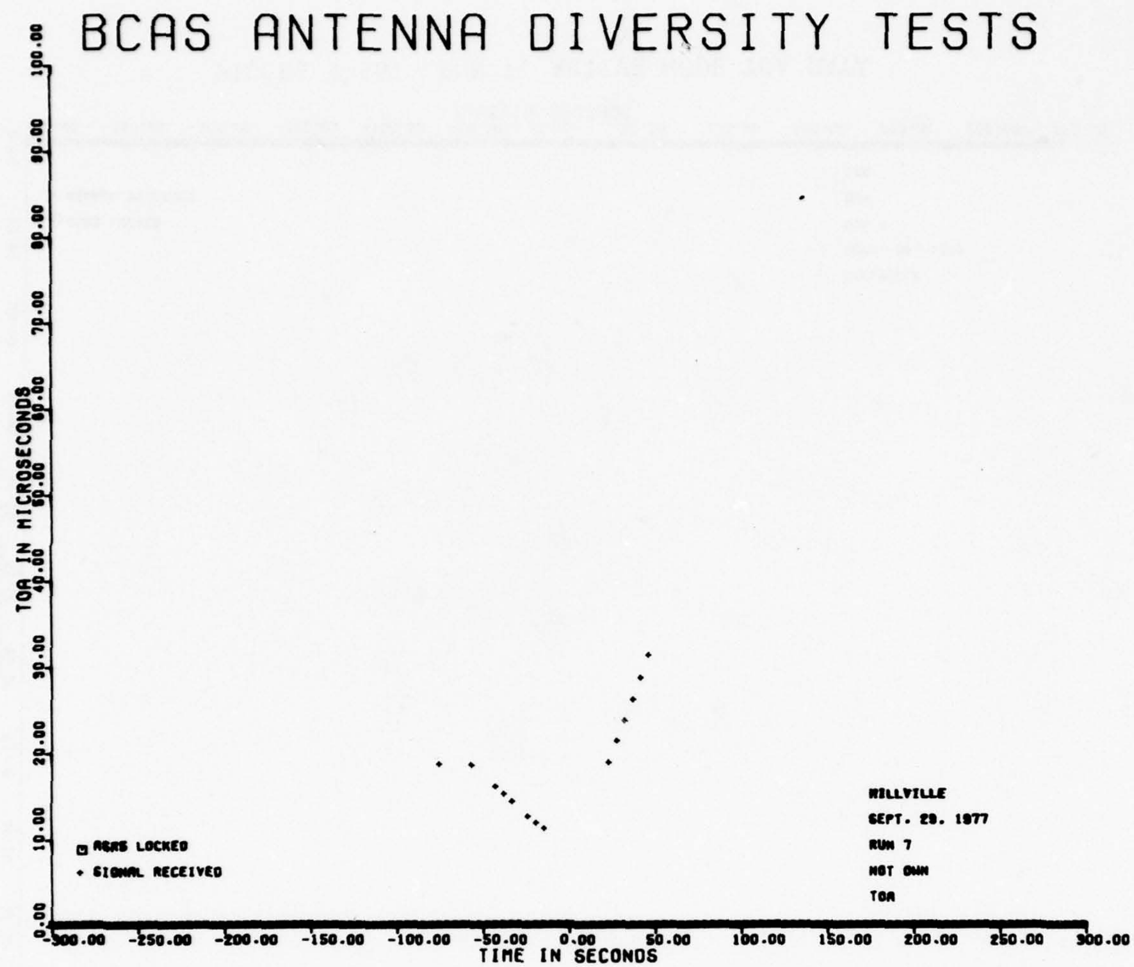


FIGURE 5-57. RUN 7, PASSIVE MODE TOA DATA

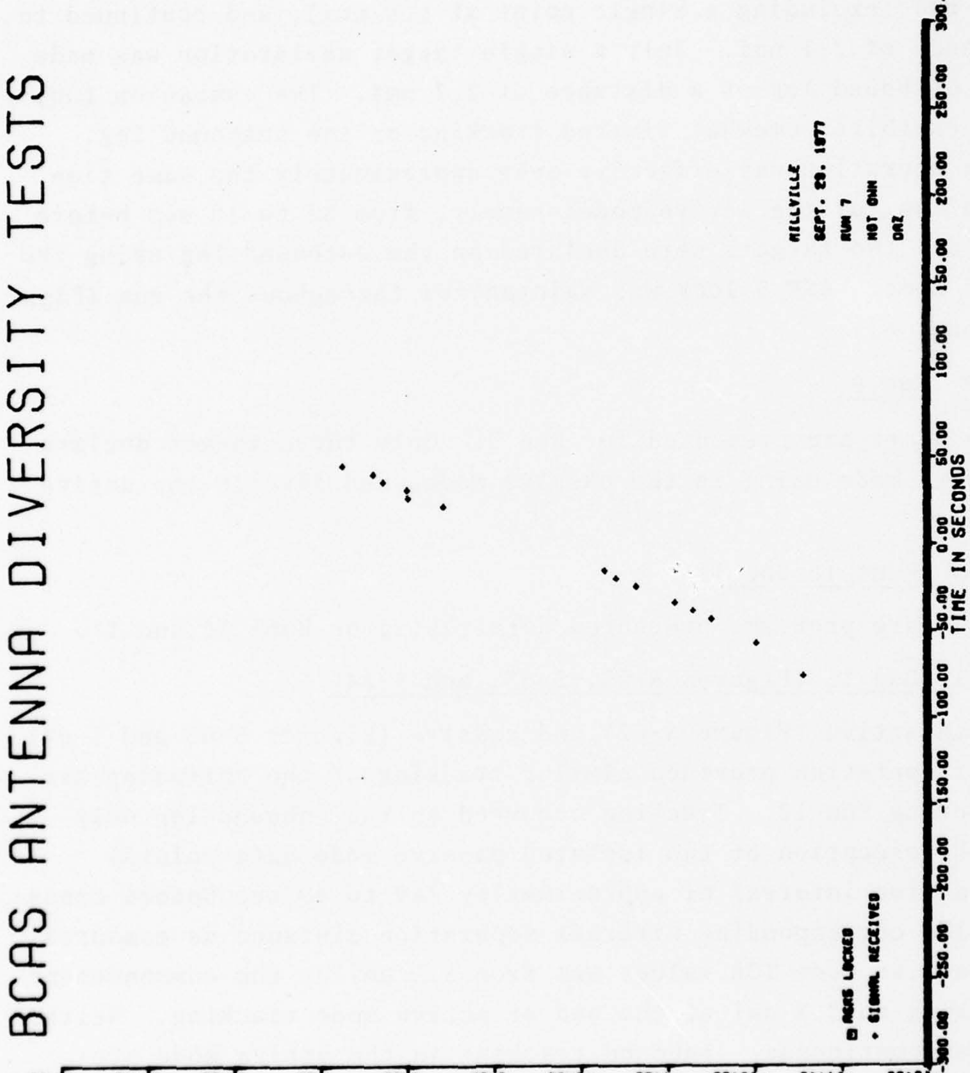


FIGURE 5-58. RUN 7, PASSIVE MODE DAZ DATA

using the ASR-5 replies was generally limited to within ± 50 sec from crossover. ASR-5 lock was maintained throughout the run.

5.2.3.8 Run 8 (Figures 5-59, 5-60, and 5-61)

Figure 5-59 shows the TOA values associated with the active mode for Run 8. Inbound tracking began at an aircraft separation of 3.9 nmi (excluding a single point at 6.8 nmi), and continued to a distance of 2.1 nmi. Only a single target declaration was made on the outbound leg at a distance of 2.7 nmi. The companion run, Run 7, exhibits somewhat limited tracking on the outbound leg. Passive operation was effective over approximately the same time interval as for the active mode; namely, from 50 to 10 sec before crossover. No targets were declared on the outbound leg using the passive mode. ASR-5 lock was maintanined throughout the run (Figs. 5-60 and 5-61).

5.2.3.9 Run 9

No plots are presented for Run 9. Only three target declarations were made using in the passive mode, and five in the active mode.

5.2.3.10 Runs 10 and 11

Software problems prevented data taking on Runs 10 and 11.

5.2.3.11 Run 12 (Figures 5-62, 5-63, and 5-64)

Both active (Figure 5-62) and passive (Figures 5-63 and 5-64) modes of operation provided similar tracking of the intruding aircraft during Run 12. Tracking occurred on the inbound leg only (with the exception of two isolated passive mode data points) during a time interval of approximatley 140 to 40 sec before crossover. The corresponding aircraft separation distance as measured by the active mode TOA values was from 5.5 nmi at the commencement of tracking to 2.3 nmi at the end of active mode tracking. Neither track was continuous. Inbound tracking in the active mode produced 26 target declarations in response to 39 interrogation bursts. Similarly in the passive mode, 18 target declarations were made in response to 24 interrogation scans of the ASR-5 radar. Lock to the ASR-5 was maintained throughout the run.

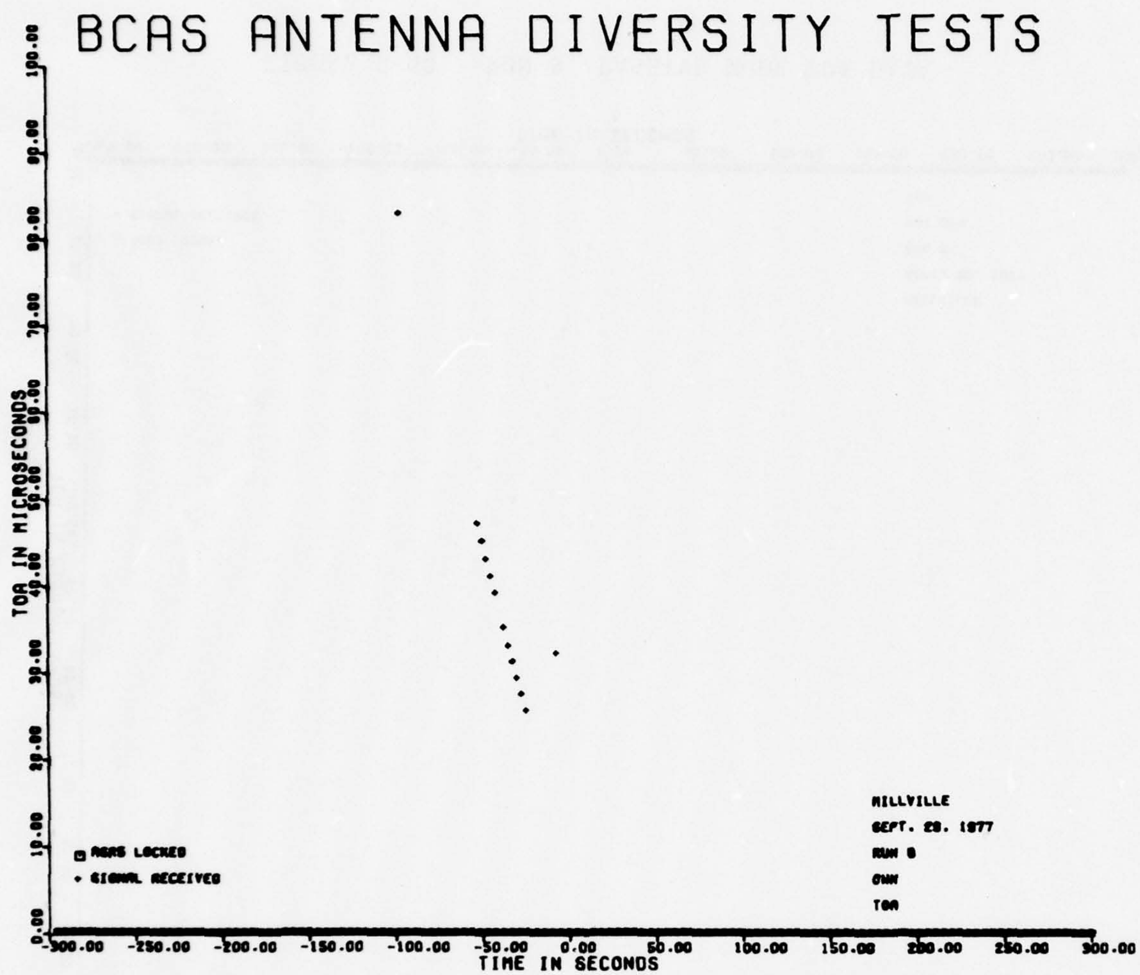


FIGURE 5-59. RUN 8, ACTIVE MODE TOA DATA

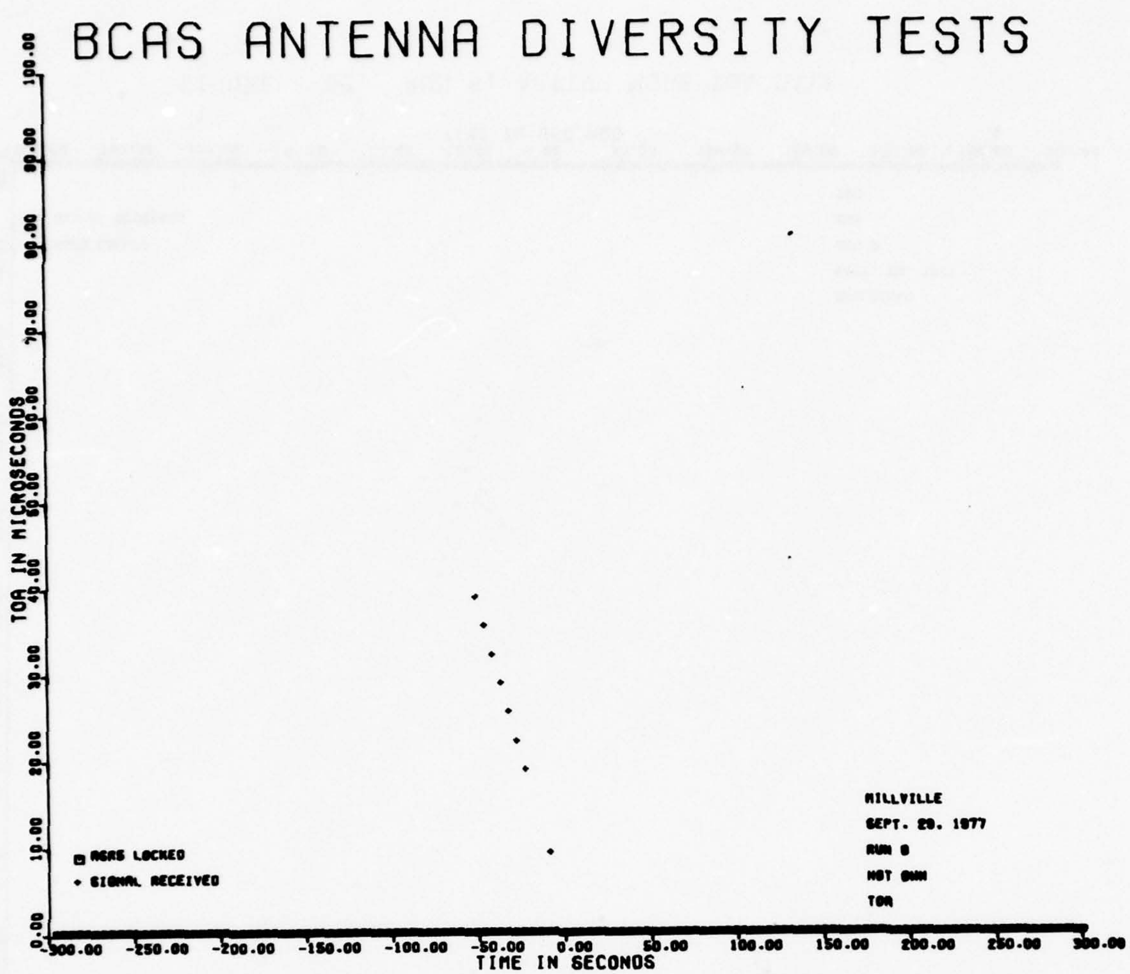


FIGURE 5-60. RUN 8, PASSIVE MODE TOA DATA

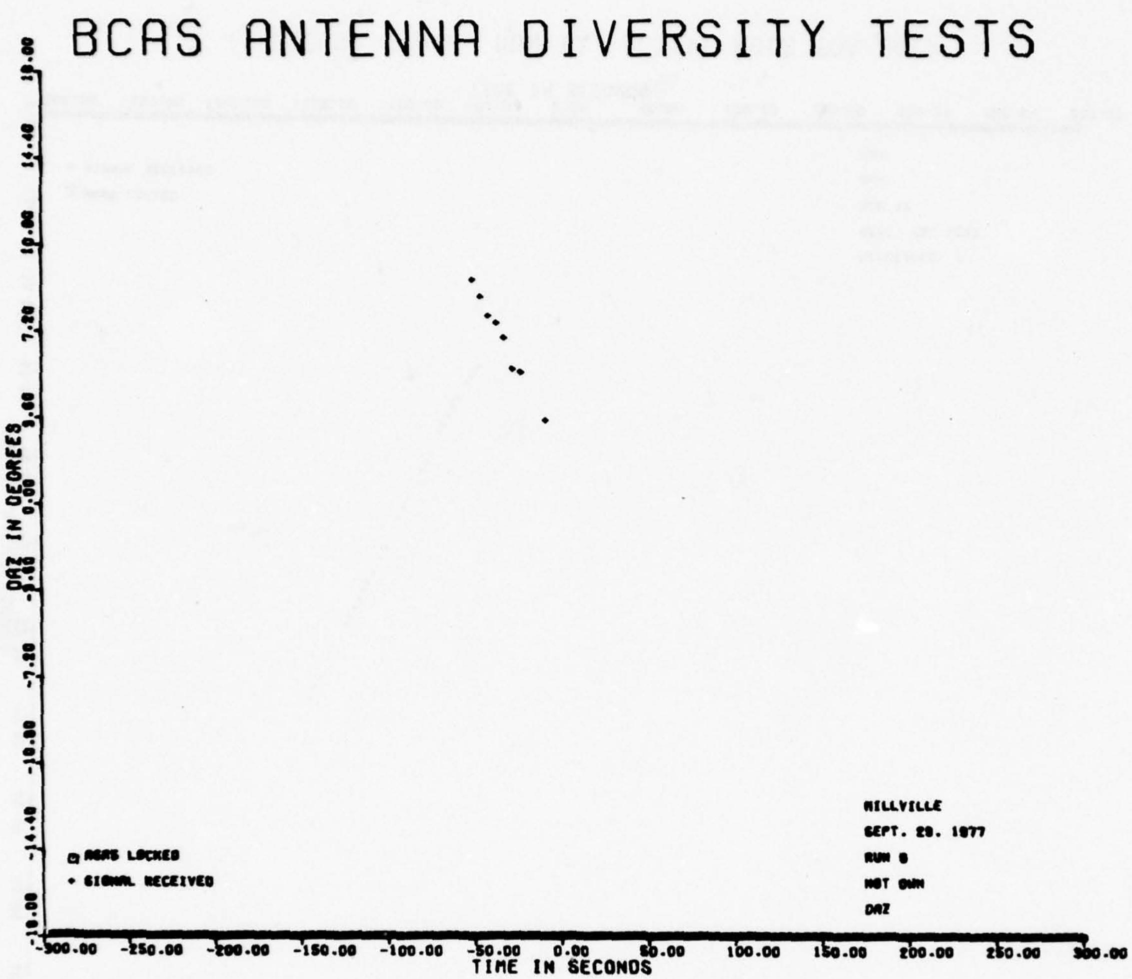


FIGURE 5-61. RUN 8, PASSIVE MODE DAZ DATA

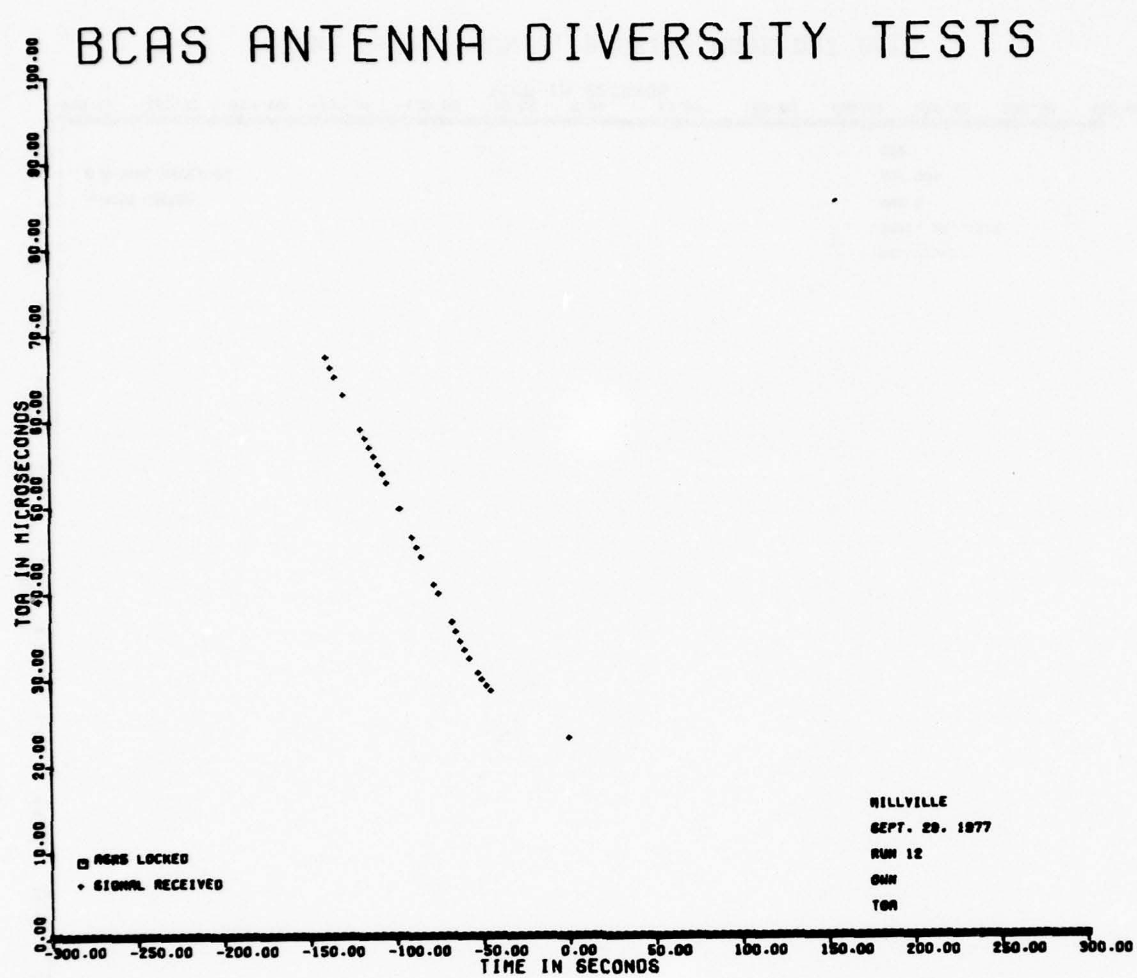


FIGURE 5-62. RUN 12, ACTIVE MODE TOA DATA

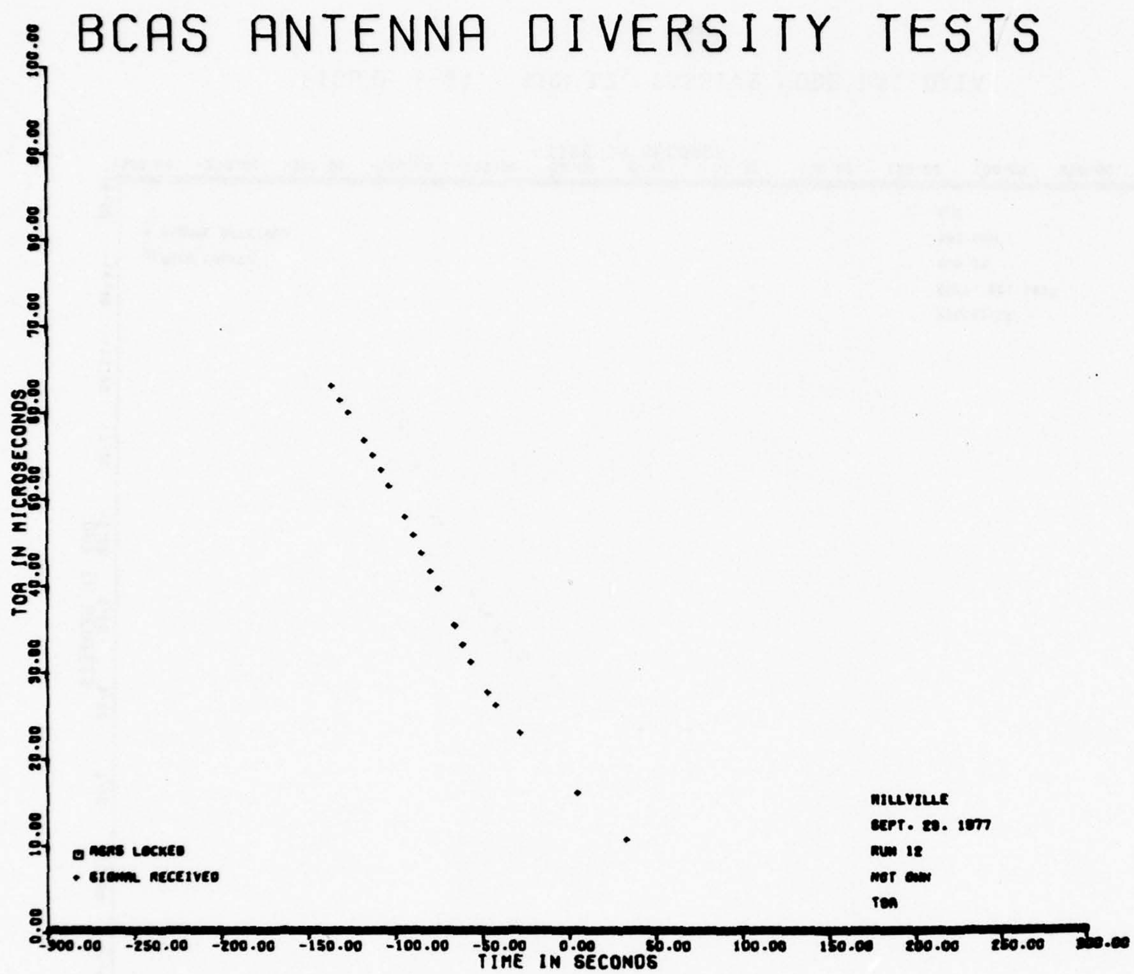


FIGURE 5-63. RUN 12, PASSIVE MODE TOA DATA

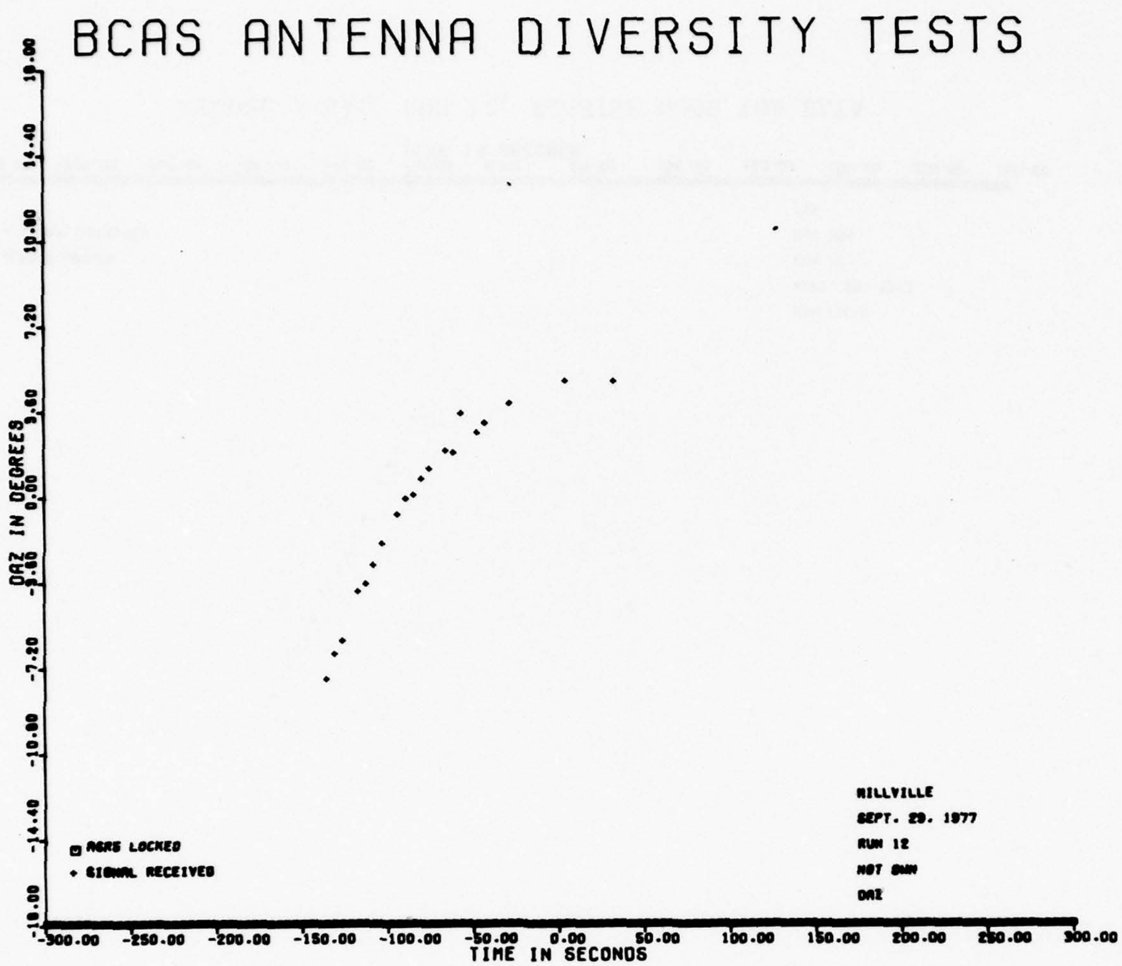


FIGURE 5-64. RUN 12, PASSIVE MODE DAZ DATA

5.2.3.12 Run 13 (Figure 5-65)

Figure 5-65 shows the TOA values for the active mode of operation in Run 13. Tracking was accomplished on the inbound leg only over aircraft separation distances ranging from 3.5 to 2.1 nmi. Tracking over this interval was quite good with only two target declarations missing. Three apparant multipath replies were received, one of which lacks a companion direct-path reply. No target declarations were made in the passive mode. ASR-5 lock was lost at approximately 2 minutes before crossover and was not reacquired. Hence, no passive mode data could have been acquired after this time.

5.2.3.13 Run 14 (Figure 5-66)

Figure 5-66 shows the TOA values corresponding to the active mode of operation on Run 14. As with its companion run, Run 13 tracking occurred only on the inbound leg (active mode), and no data were obtained in the passive mode. The aircraft separation distance ranged from 5.0 nmi (first target declaration) to 1.8 nmi (last target declaration). Tracking on Run 14 was much less consistent than on the previous run, with only 13 target declarations being made in response to 38 active mode interrogation bursts. ASR-5 lock was not acquired until approximately 2-1/2 minutes after crossover. Consequently, no passive mode data could have been acquired prior to this time.

5.2.3.14 Run 15 (Figures 5-67, 5-68, and 5-69)

The intruding aircraft was tracked from 4.9 to 1.8 nmi on the inbound leg in the active mode as shown in Figure 5-67. The corresponding time interval over which tracking took place was from 103 to 18 sec before crossover. Passive mode tracking of the intruding aircraft is shown in Figures 5-68 and 5-69 and occurred between 98 and 9 sec before crossover. The BCAS was unable to track the intruding aircraft in either mode on the outbound leg. Both modes showed intermittent tracking on the inbound leg. ASR-5 lock was maintained through the run with the exception of an interval of approximately 40 seconds beginning approximately 3 minutes after crossover.

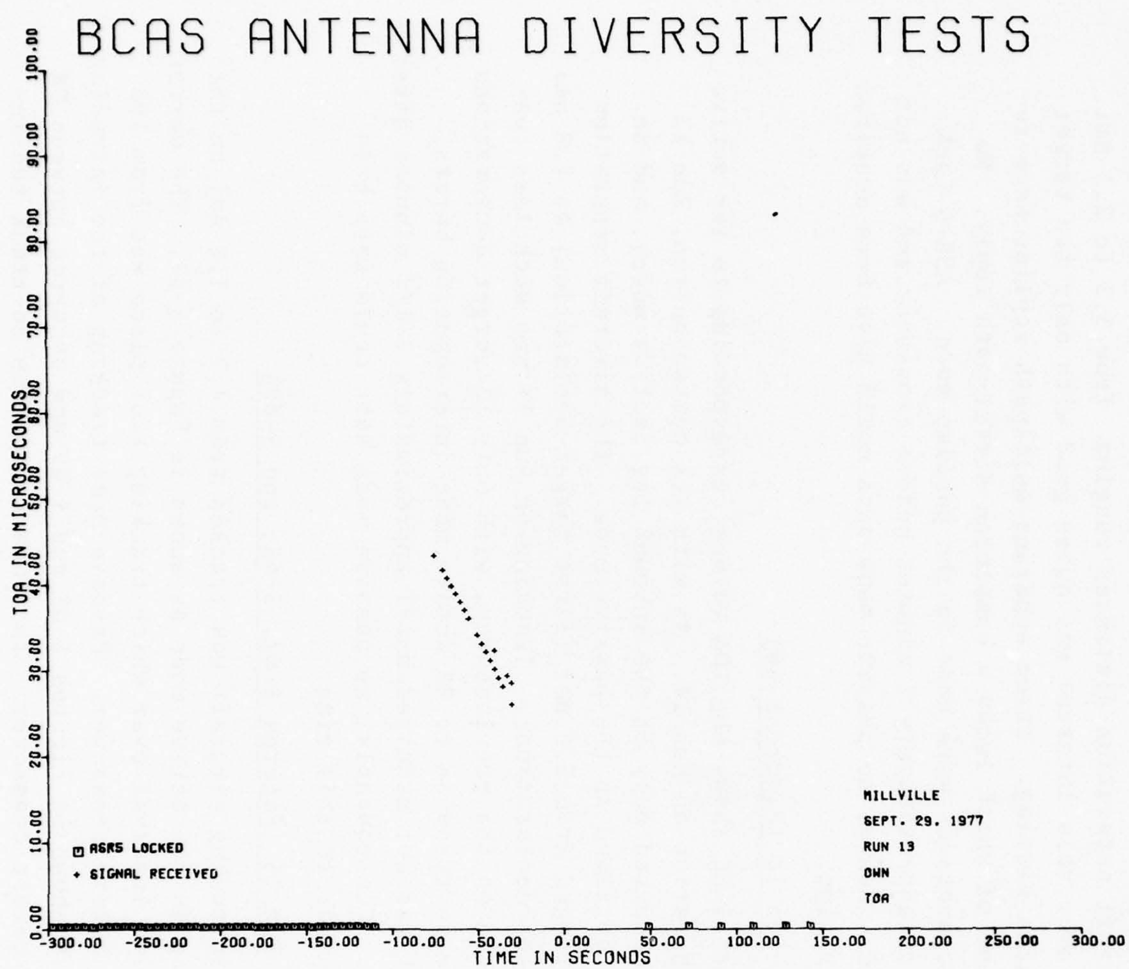


FIGURE 5-65. RUN 13, ACTIVE MODE TOA DATA

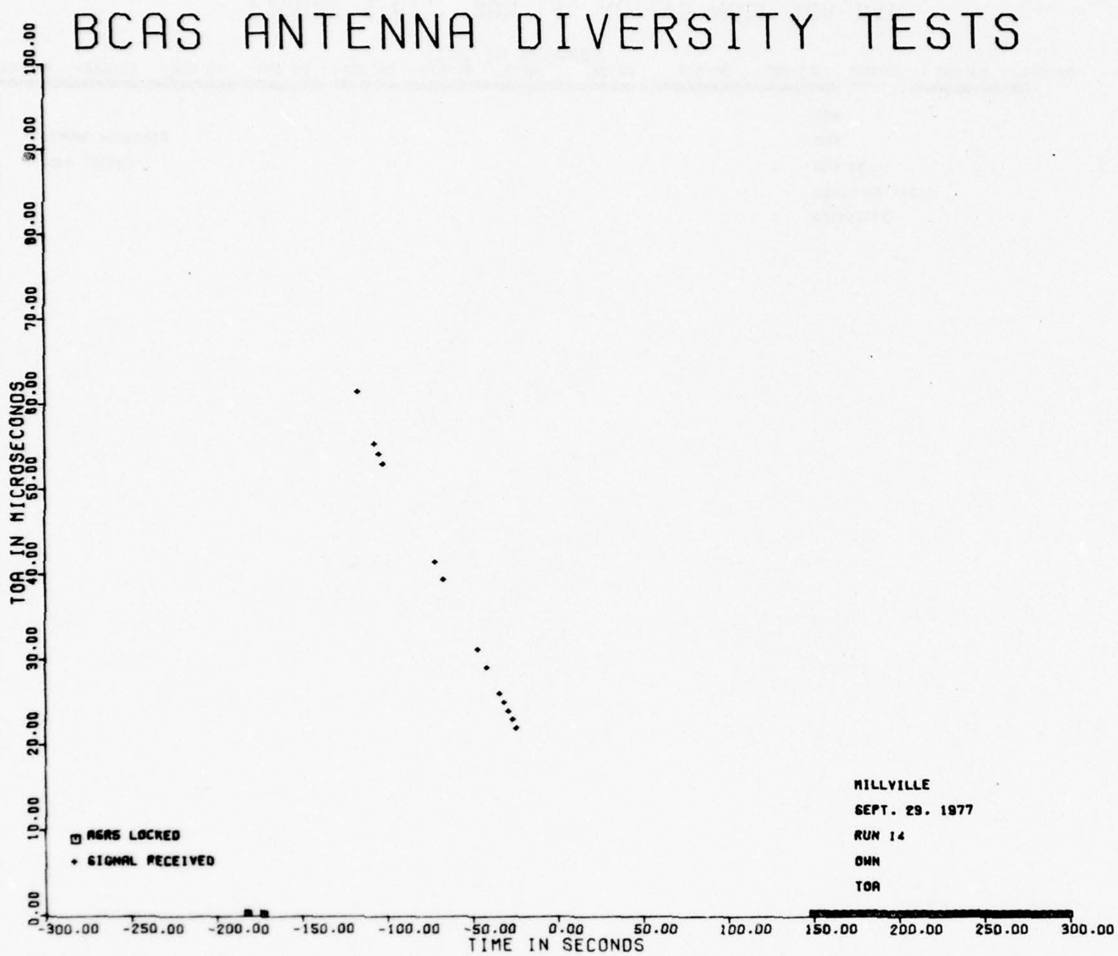


FIGURE 5-66. RUN 14, ACTIVE MODE TOA DATA

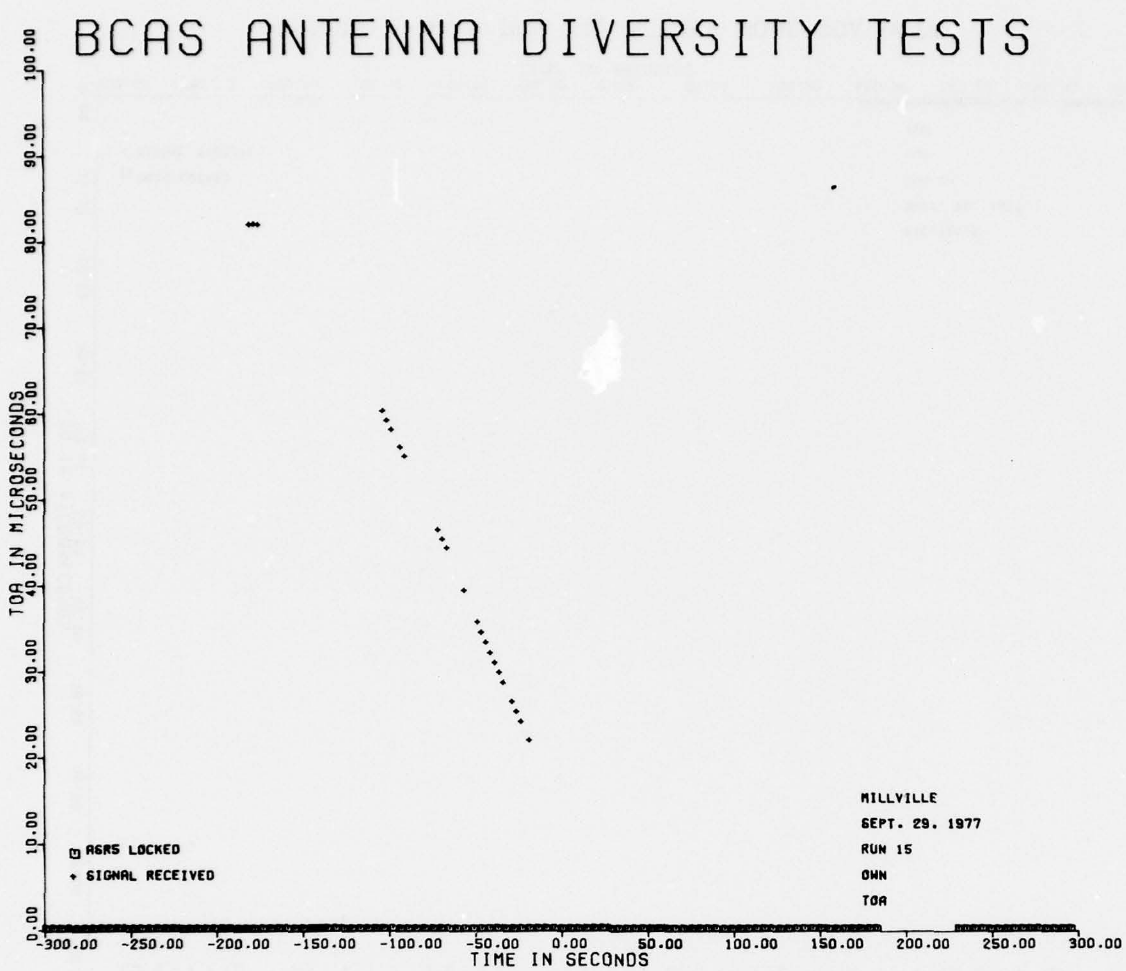


FIGURE 5-67. RUN 15, ACTIVE MODE TOA DATA

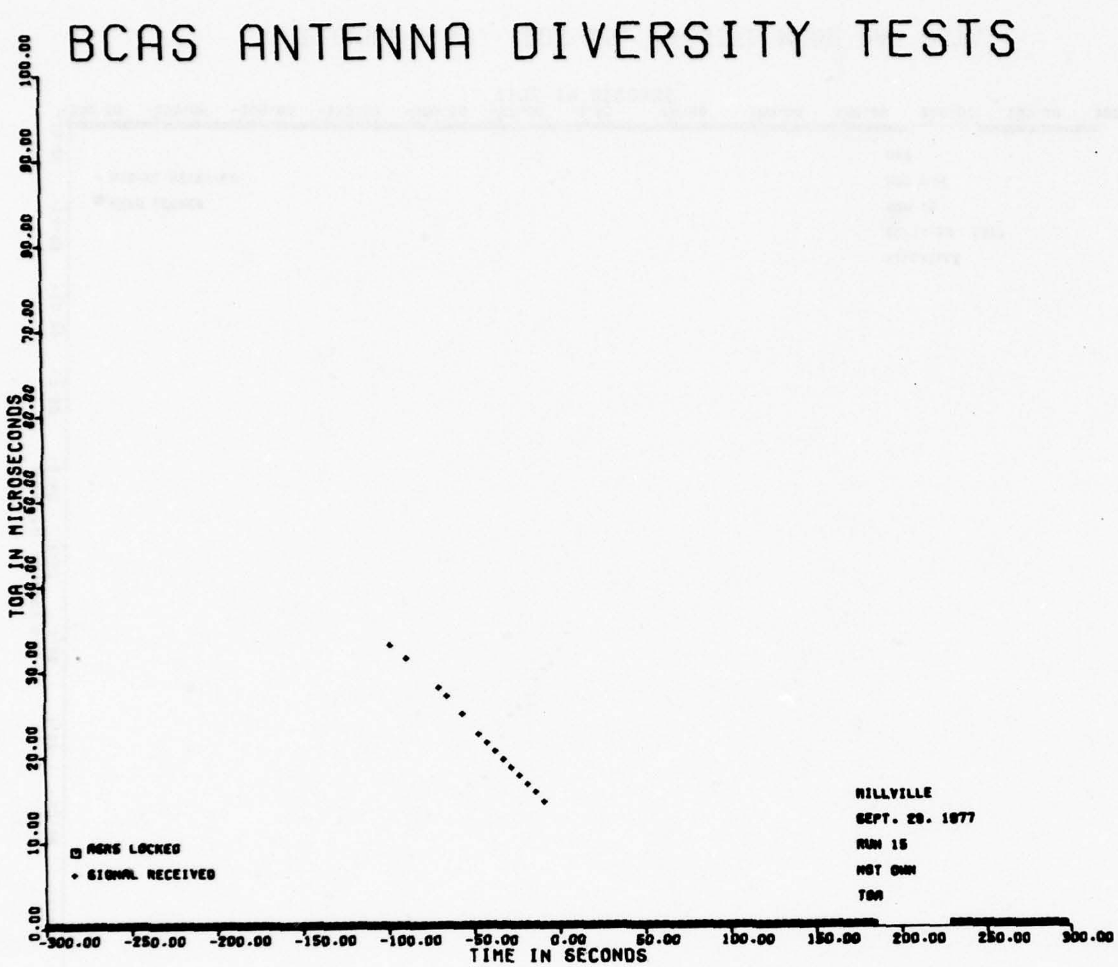


FIGURE 5-68. RUN 15, PASSIVE MODE TOA DATA

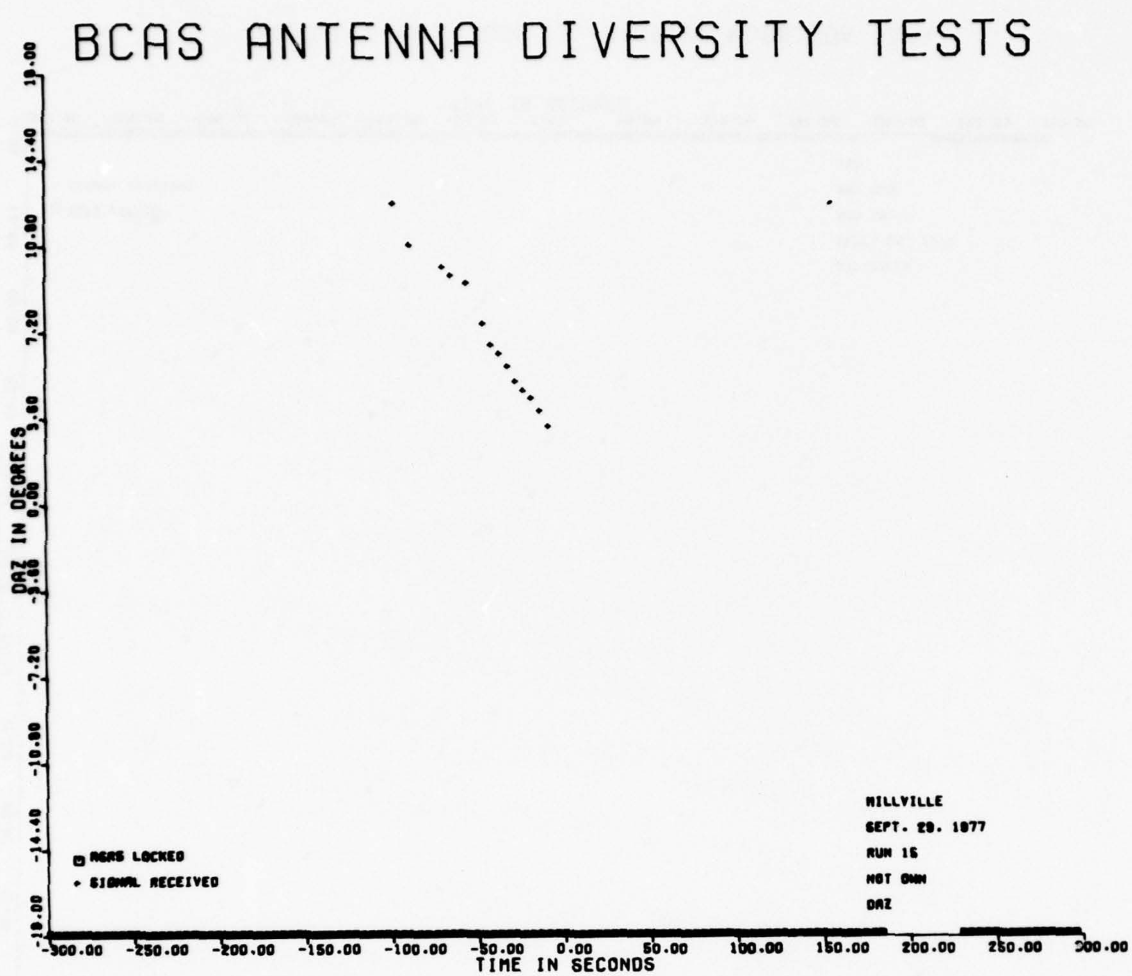


FIGURE 5-69. RUN 15, PASSIVE MODE DAZ DATA

5.2.3.15 Run 16 (Figures 5-70, 5-71 and 5-72)

Figure 5-70 shows the active mode TOA values for Run 16. Only five target declarations were made inbound, with the points occurring at three widely separated regions of the inbound leg. Outbound tracking was limited to 3 target declarations occurring approximately 30 seconds after crossover. Passive mode operation was a little better, with 4 of 5 target declarations taking place between 130 to 100 seconds before crossover, and 4 of the 5 outbound target declarations occurring between 20 and 40 seconds after crossover. ASR-5 lock was maintained throughout the run. (Figs. 5-71 and 5-72).

5.2.3.16 Run 17 (Figures 5-73, 5-74, and 5-75)

Only three isolated target declarations were made in the active mode on the inbound leg on Run 17 as shown in Figure 5-73. The intruding aircraft was, however, tracked from 1.8 to 3.3 nmi on the outbound leg. The passive mode provided tracking on the inbound leg, but was unable to track the intruding aircraft on the outbound leg. This result is somewhat unusaul, in that both modes usually show tracking over similar portions of the run rather then in complementary segments as in the case of this run. ASR-5 lock was maintained throughout the run except for two scans occurring approximately 2-1/2 minutes after crossover (Figs. 5-74 and 5-75).

5.2.3.17 Run 18 (Figures 5-76, 5-77, and 5-78)

Relatively few data points (target declarations) were obtained in either mode during Run 18. Both modes favor tracking on the occurring between approximately 40 and 70 sec. after crossover. ASR-5 lock was maintained throughout the run. (See Figs. 5-76, 5-77, and 5-78.)

5.2.3.18 Run 19 (Figure 5-79)

Figure 5-79 shows data acquired in the active mode during Run 19. Only three target declarations were made on the inbound leg although reasonably good tracking was obtained on the outbound leg at separations from 1.8 to 3.2 nmi. The BCAS was unable to detect the intruding aircraft, eigher inbound or outbound, using replies elicited by the ASR-5 (i.e., passive mode). ASR-5 lock was,

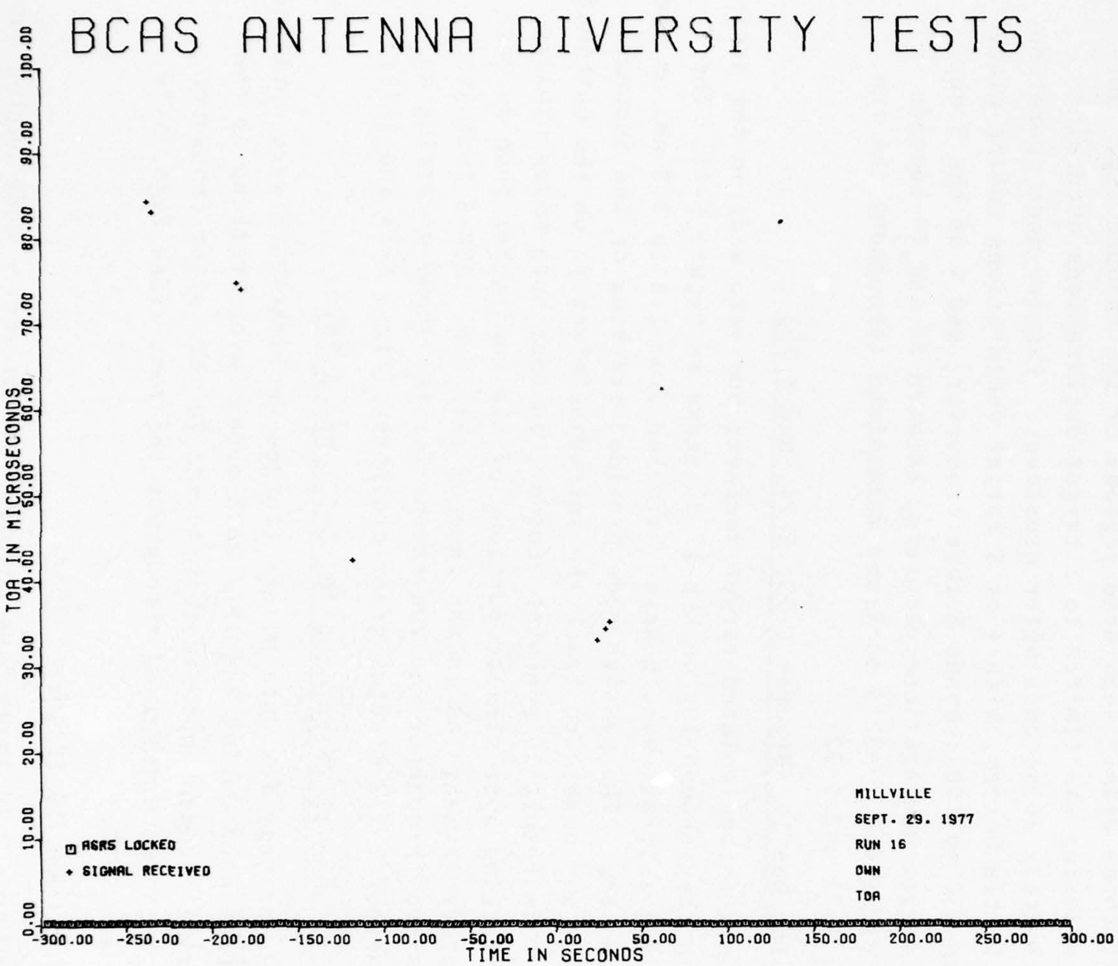


FIGURE 5-70. RUN 16, ACTIVE MODE TOA DATA

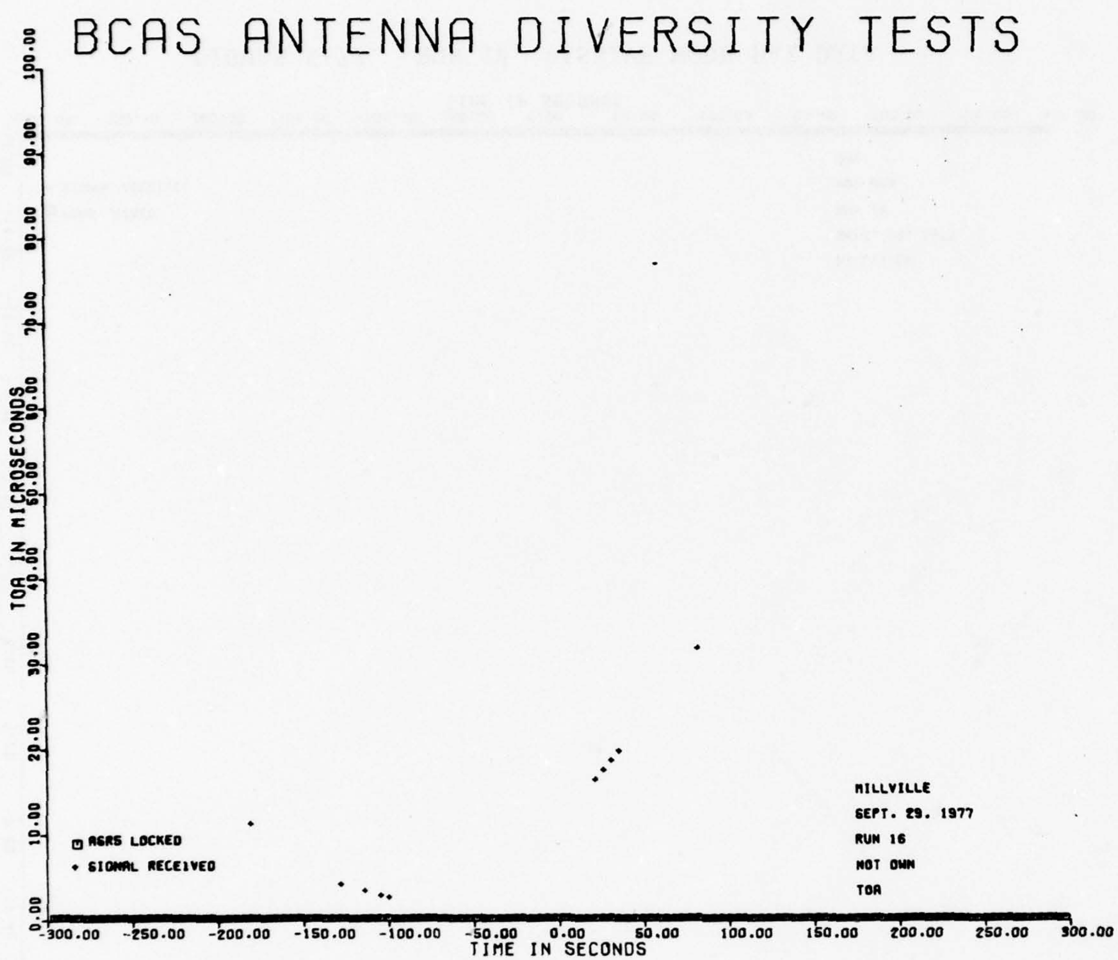


FIGURE 5-71. RUN 16, PASSIVE MODE TOA DATA

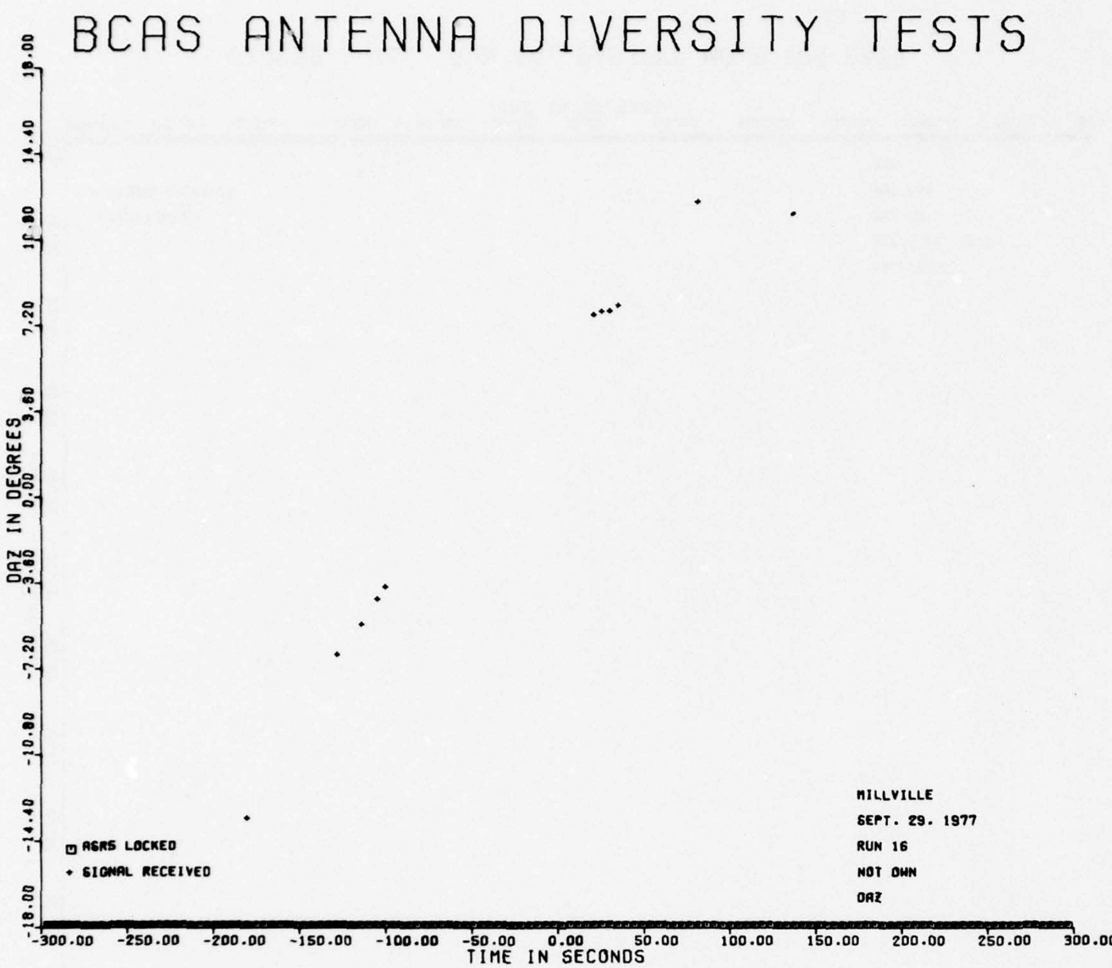


FIGURE 5-72. RUN 16, PASSIVE MODE DAZ DATA

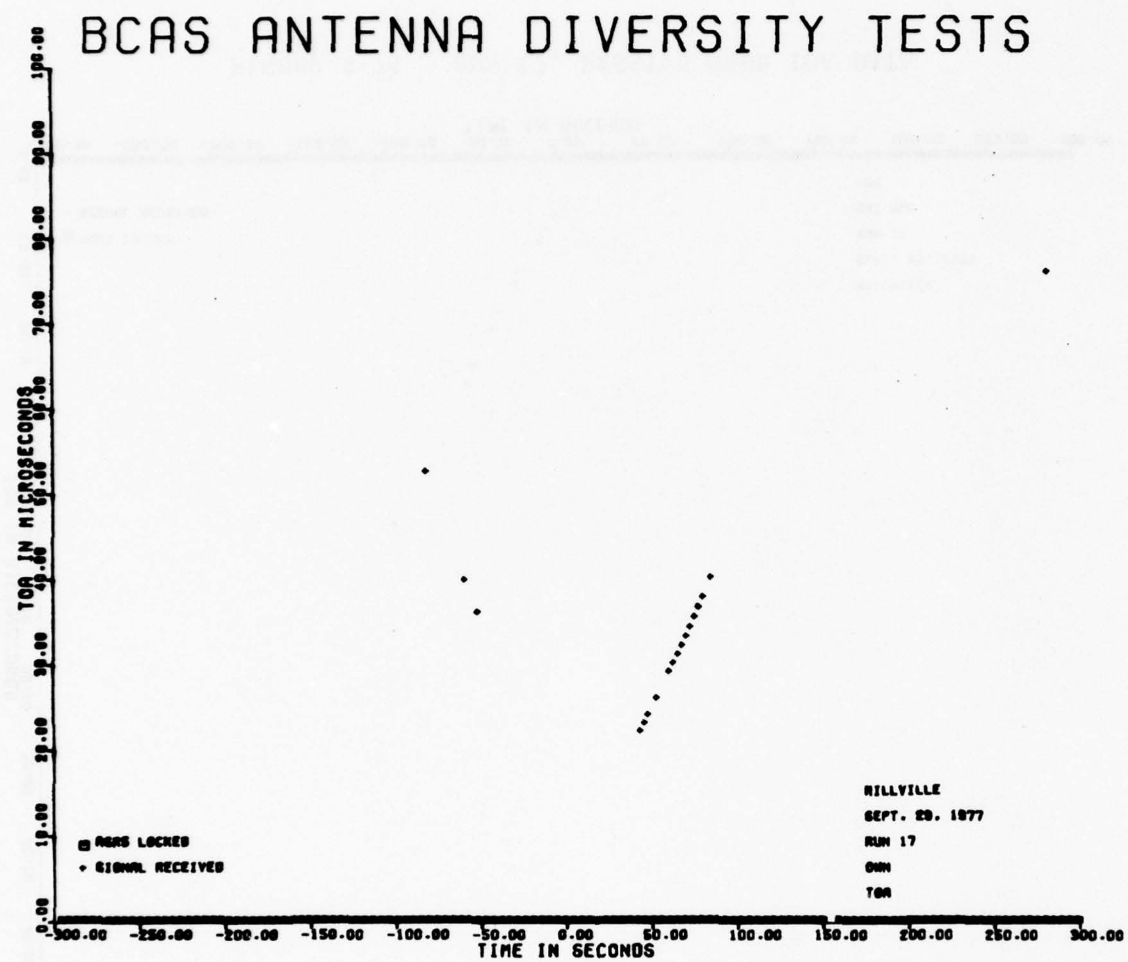


FIGURE 5-73. RUN 17, ACTIVE MODE TOA DATA

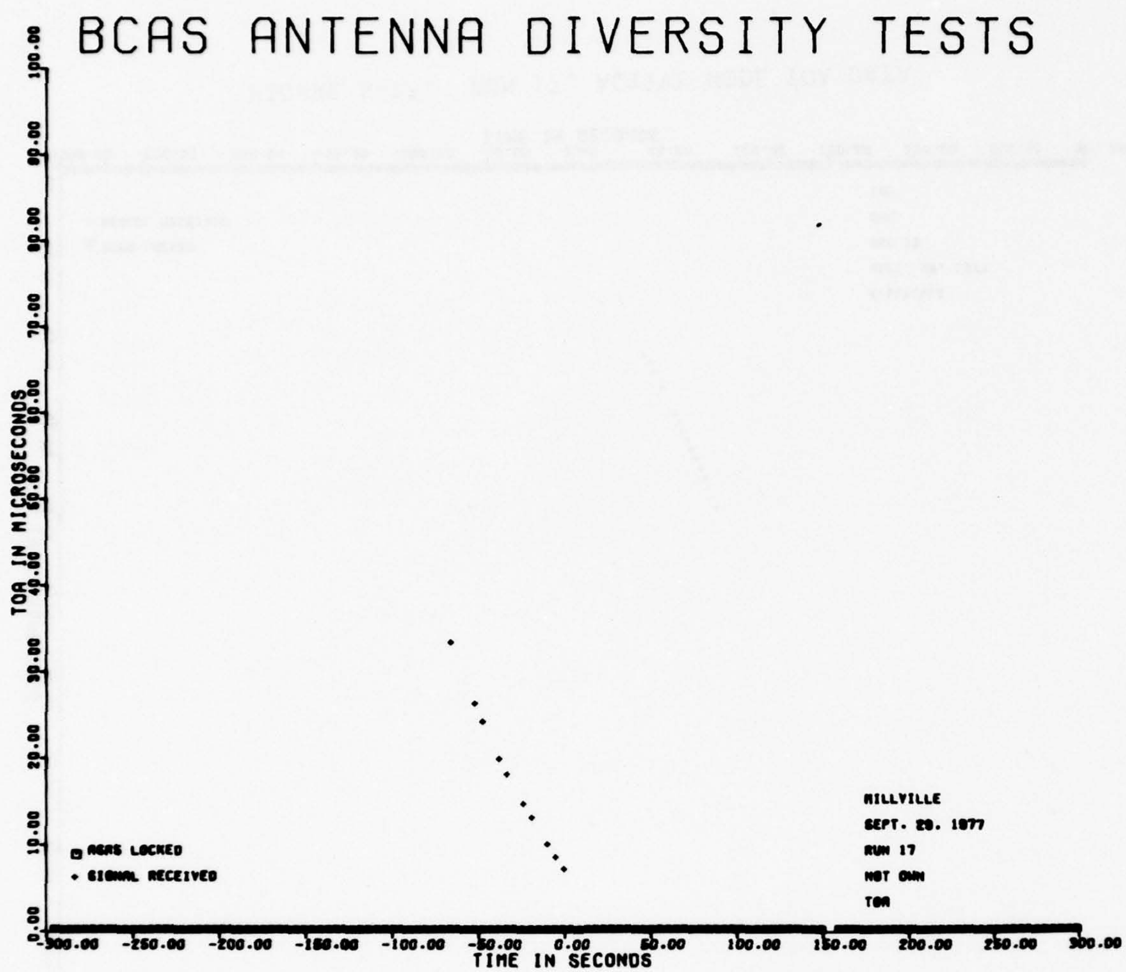


FIGURE 5-74. RUN 17, PASSIVE MODE TOA DATA

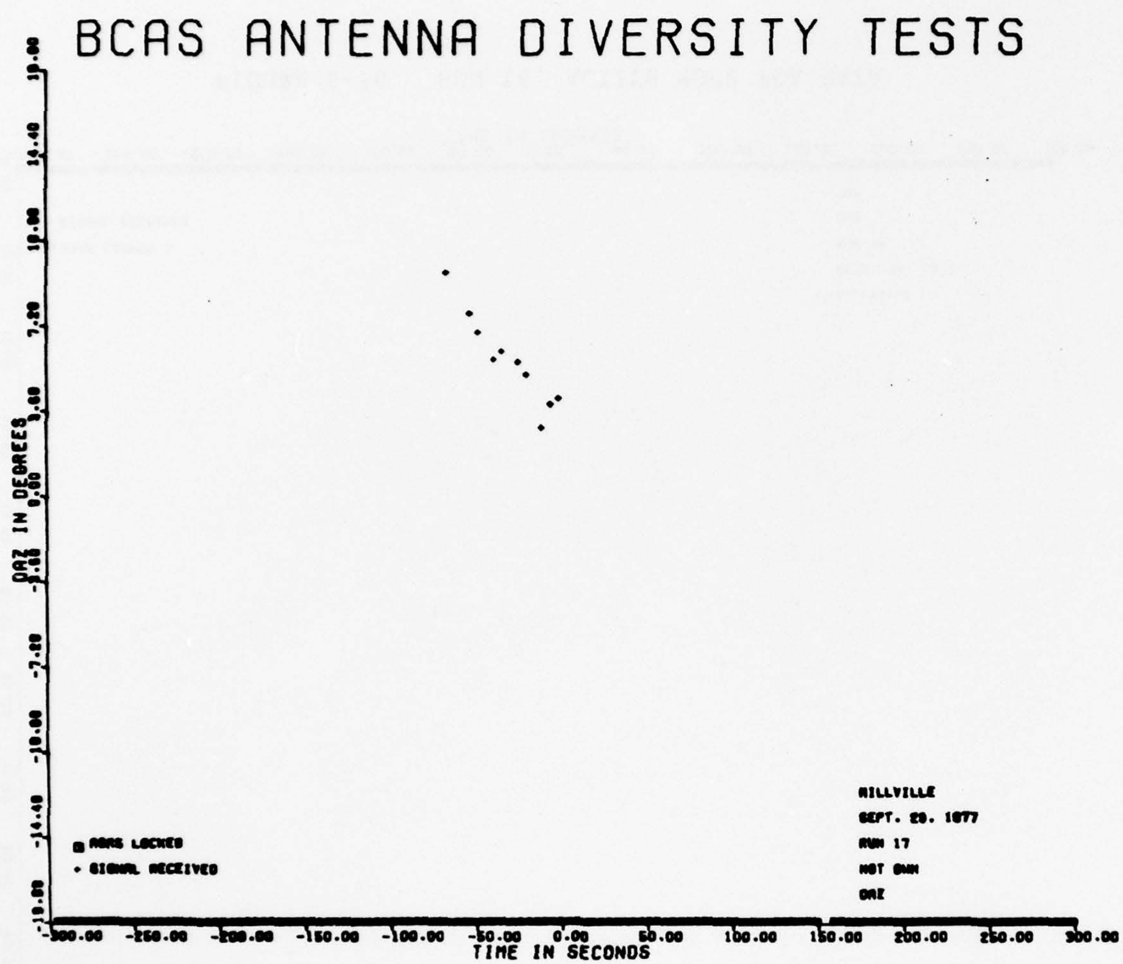


FIGURE 5-75. RUN 17, PASSIVE MODE DAZ DATA

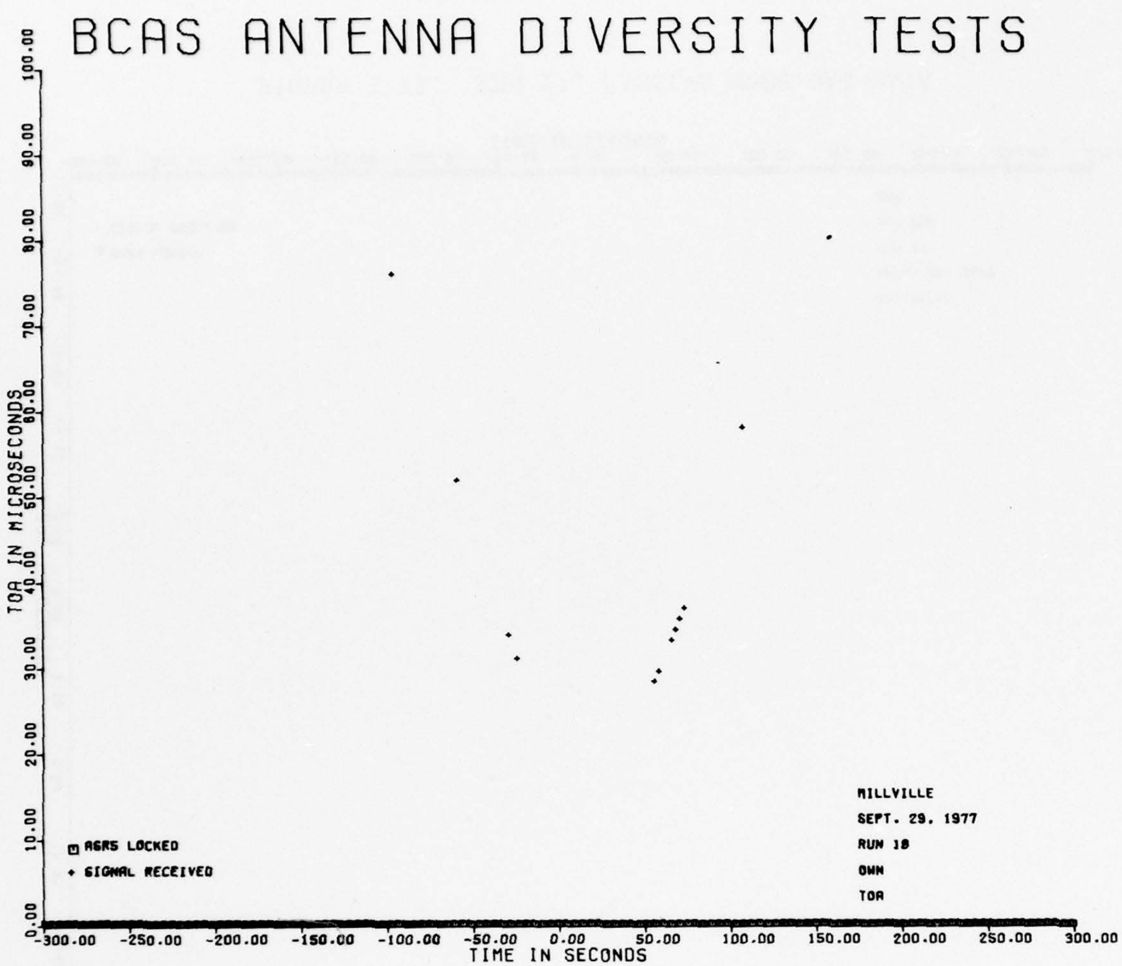


FIGURE 5-76. RUN 18, ACTIVE MODE TOA DATA

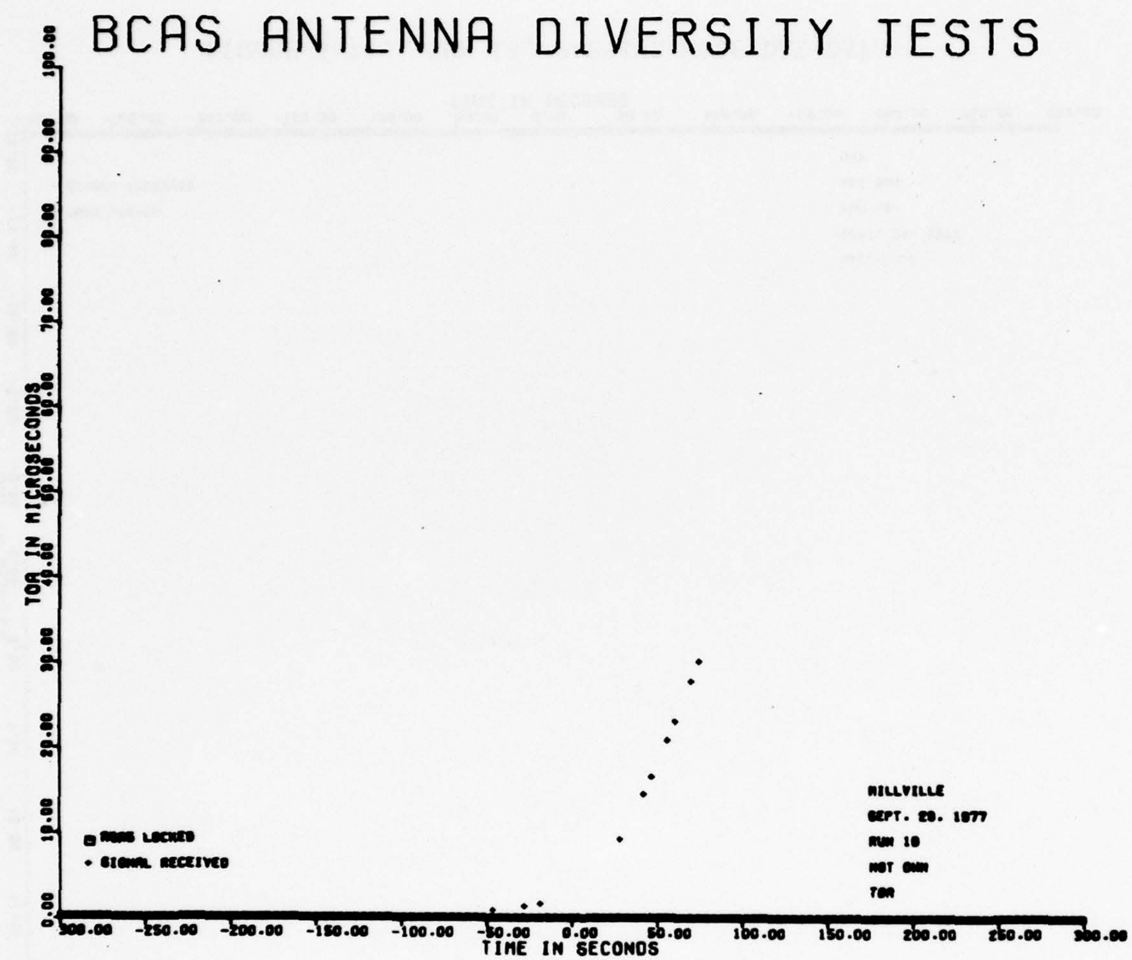


FIGURE 5-77. RUN 18, PASSIVE MODE TOA DATA

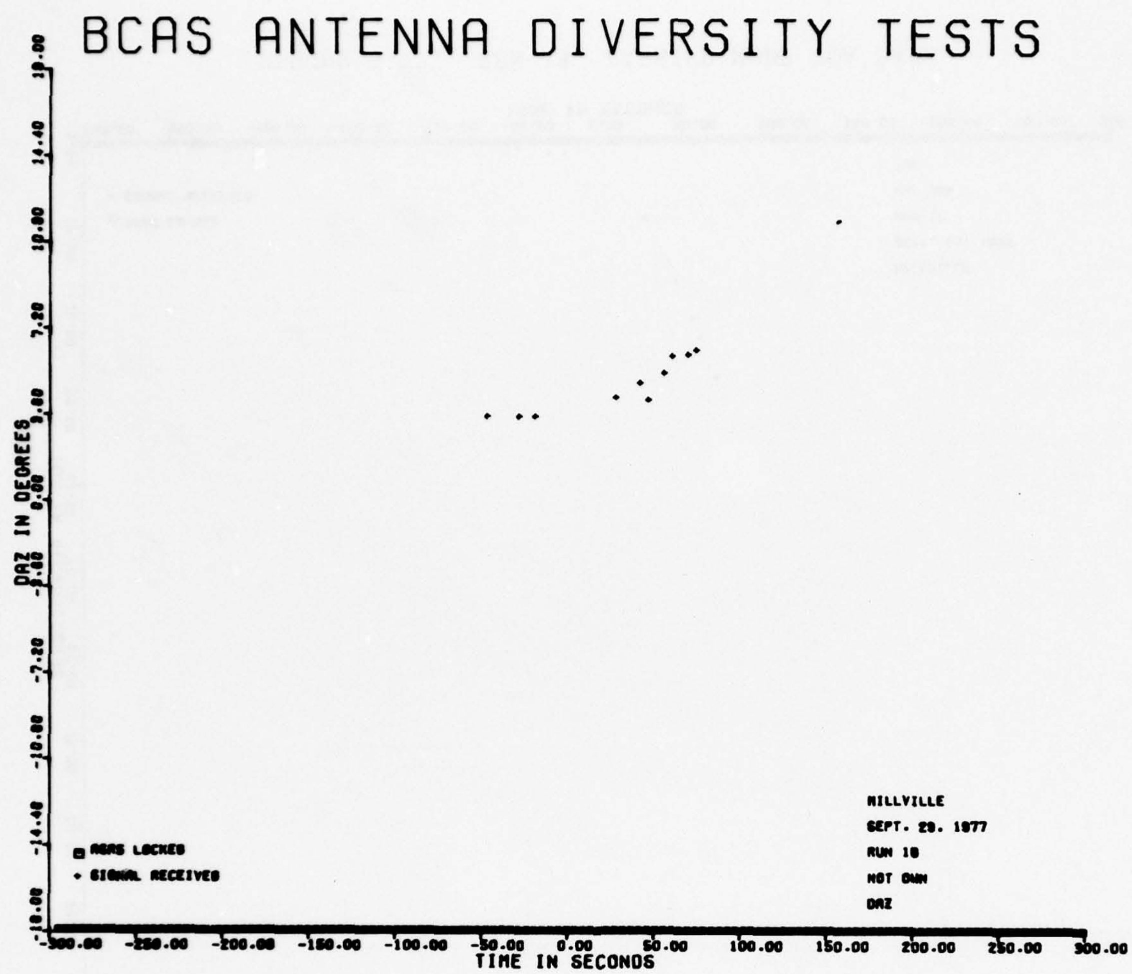


FIGURE 5-78. RUN 18, PASSIVE MODE DAZ DATA

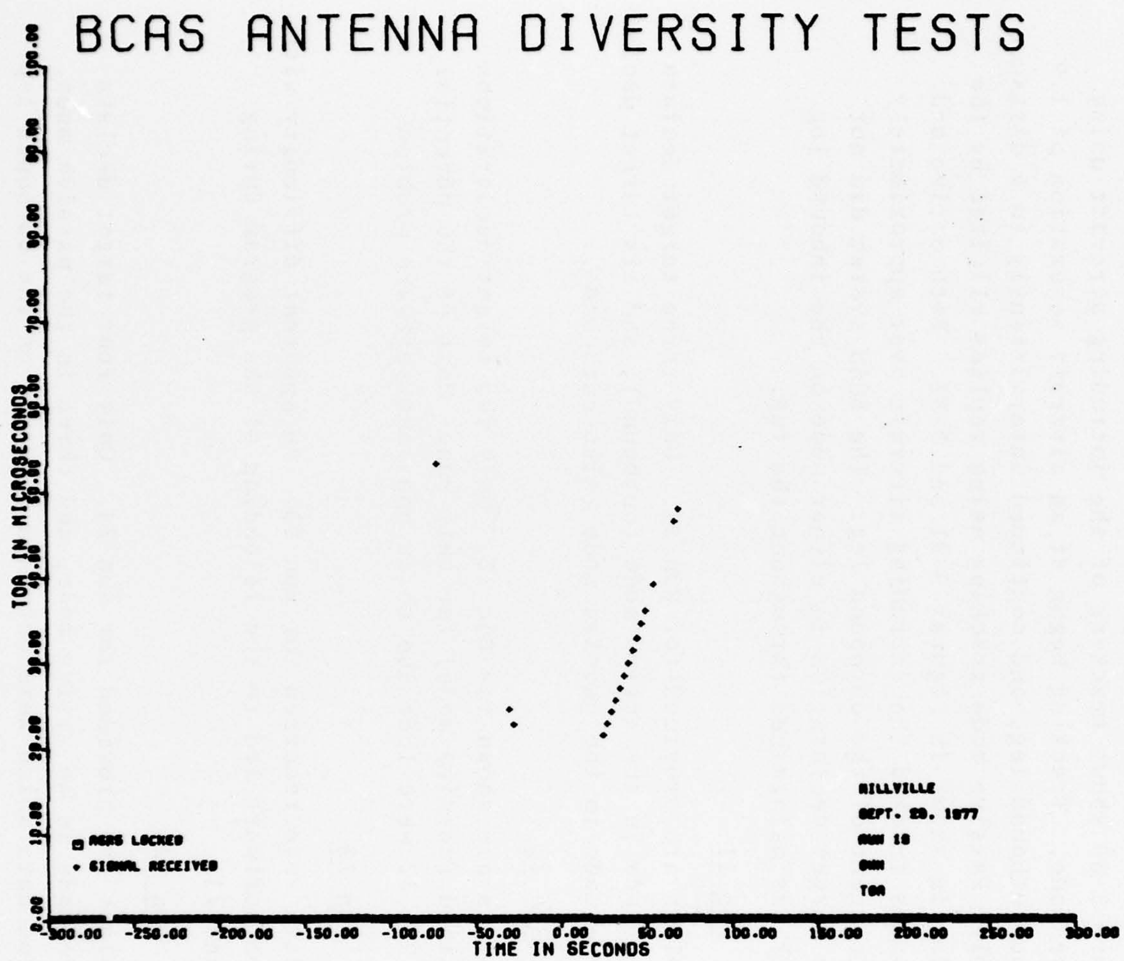


FIGURE 5-79. RUN 19, ACTIVE MODE TOA DATA

however, maintained throughout the run but for two lost scans at the very beginning.

5.2.3.19 Run 20 (Figures 5-80, 5-81, and 5-82)

Figure 5-80 shows tracking of the intruding aircraft using the active mode. Tracking began at an aircraft separation of 1.9 nmi on the outbound leg, and continued intermittently to a distance of 4.6 nmi.. Passive mode tracking using replies elicited by the ASR-5 radar is shown in Figures 5-81 and 5-82. Both active and passive modes tracked the intruding aircraft over approximately the same segment of the outbound leg. The BCAS system did not provide a target declaration in either mode on the inbound leg. ASR-5 lock was maintained throughout the run.

5.2.3.20 Run 21

No plots are provided for Run 21. Only three target declarations were made in the active mode (outbound), and six target declarations were made in the passive mode (also outbound).

5.2.3.21 Run 22

No plots are shown for Run 22. Only two target declarations were obtained (passive mode) for this run. Most of the potential data for Run 22 were lost due to an apparent software problem.

5.2.3.22 Run 23

No data were recorded for Run 23. An apparent difficulty with the system software led to the reloading of the program during Runs 22 and 23.

5.2.3.23 Run 24

No plots are provided for Run 24. Only four target declarations were made in the active mode, and three in the passive mode. The limited data which were obtained occurred on the outbound leg.

5.2.3.24 Run 25 (Figures 5-83, 5-84, and 5-85)

Run 25 is not part of the daisy over figure eight tests. Based upon observation of the BCAS displays, it appeared that very few target declarations were being made during 24 run pattern. Con-

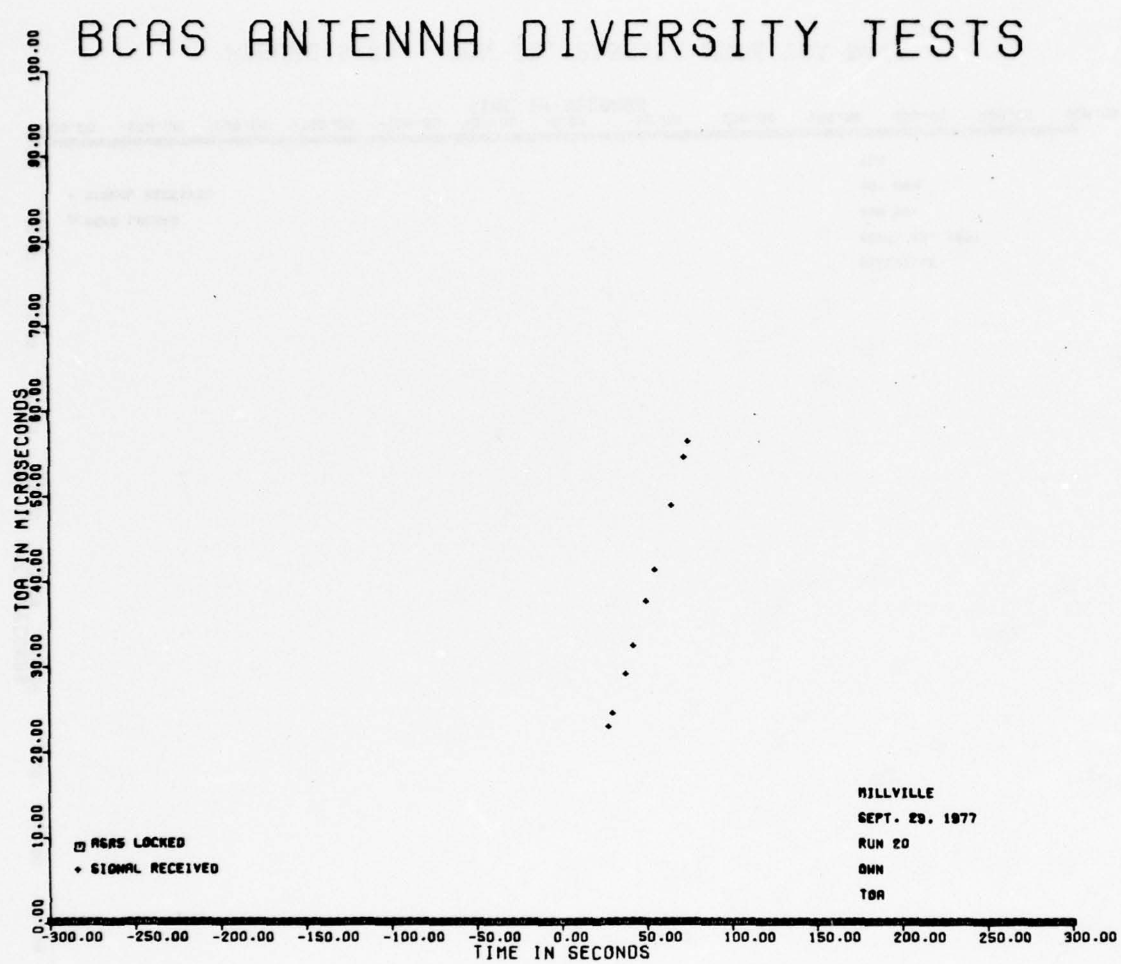


FIGURE 5-80. RUN 20, ACTIVE MODE TOA DATA

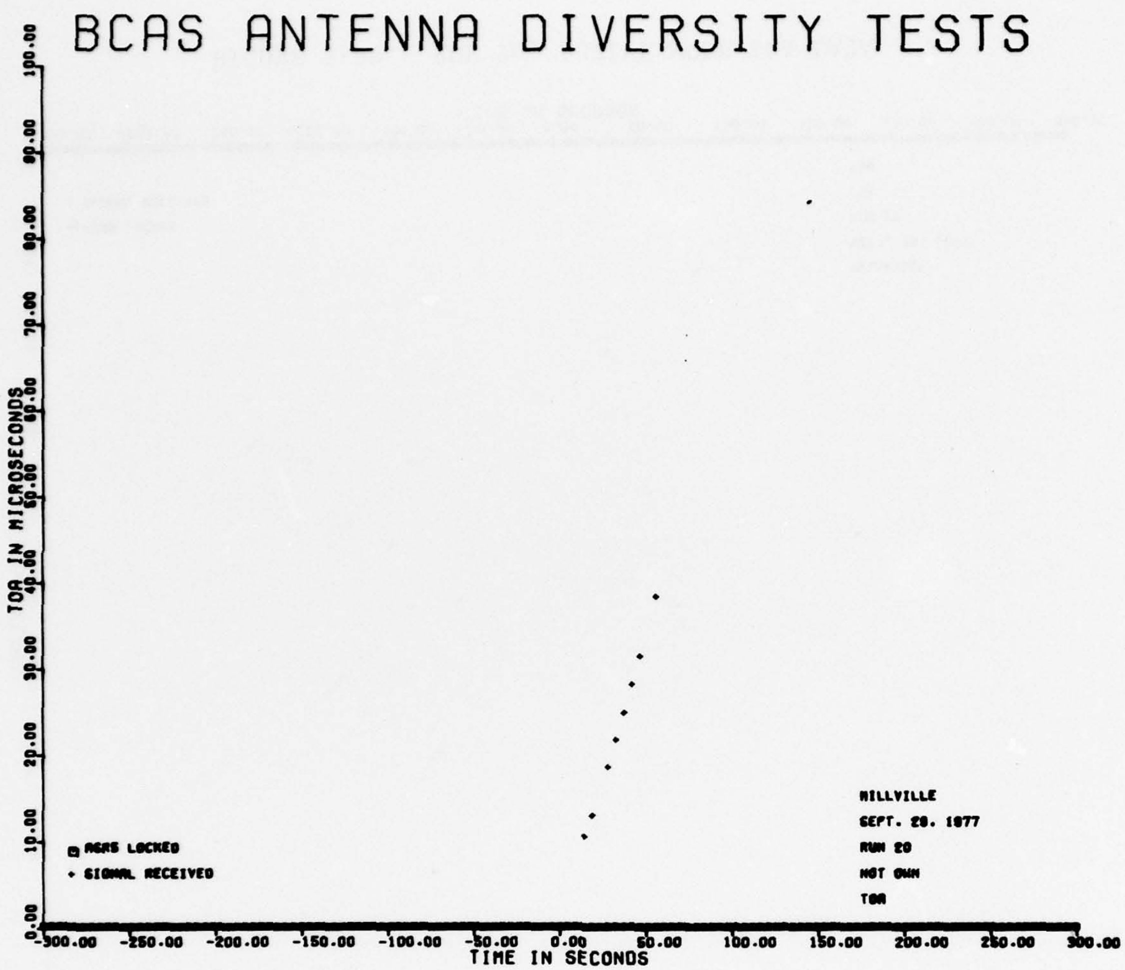


FIGURE 5-81. RUN 20, PASSIVE MODE TOA DATA

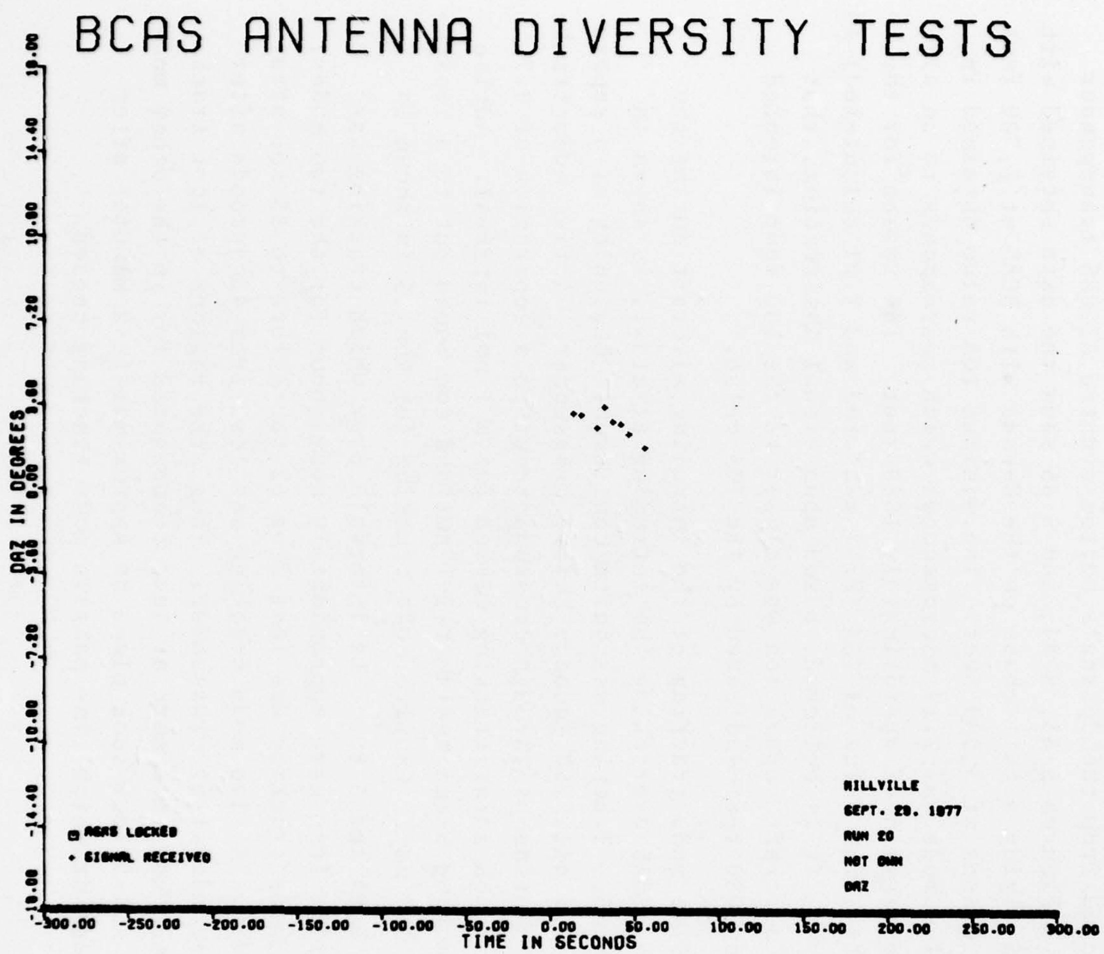


FIGURE 5-82. RUN 20, PASSIVE MODE DAZ DATA

sequently, an attempt was made to verify system operation by flying the BCAS aircraft below the intruding aircraft, the Cessna 172, at an altitude separation of 500 feet. This would place the BCAS aircraft in a position where reasonably good antenna coverage could be expected from the Cessna's bottom-mounted ATCRBS transponder antenna. Figures 5-83, 5-84, and 5-85 show the data obtained with the BCAS flying a tail chase on the Cessna with BCAS at 2,500 feet and the Cessna at 3,000 feet. The minimum TOA value obtained in the active mode was 2.17 microseconds which corresponds to an aircraft separation of approximately 1080 feet. The reason for the apparently high value of TOA (2.17 measured and 1.01 calculated) is not known. It is believed, based upon visual observation, that minimum aircraft separation was closer to the 500 feet intended than the 1080 feet indicated by the TOA value.

Active mode tracking of the intruding aircraft during the approach, BCAS overtaking the intruding aircraft, is shown in Figure 5.83. Tracking was quite consistent, beginning at a separation of 2.1 nmi, 157 seconds before crossunder. Active mode tracking was continuous through crossunder out to a separation of 0.7 nmi, at which point tracking ceased for a 1-nmi interval. Active mode tracking began again at 1.7 nmi and continued out to a separation of 2.0 nmi. Passive mode tracking for Run 25 is shown in Figures 5-84 and 5-85. The intervals over which tracking was temporarily lost were approximately contiguous for the two modes. Passive mode tracking was lost from 62 sec before to 55 sec after crossunder. Active mode tracking was lost from 42 seconds after to 95 seconds after crossunder. Thus, the regions of lost tracking in one mode are more or less compensated for in the other mode. Loss of ASR-5 lock took place at approximately 2 minutes after crossunder at which time passive mode tracking ceased.

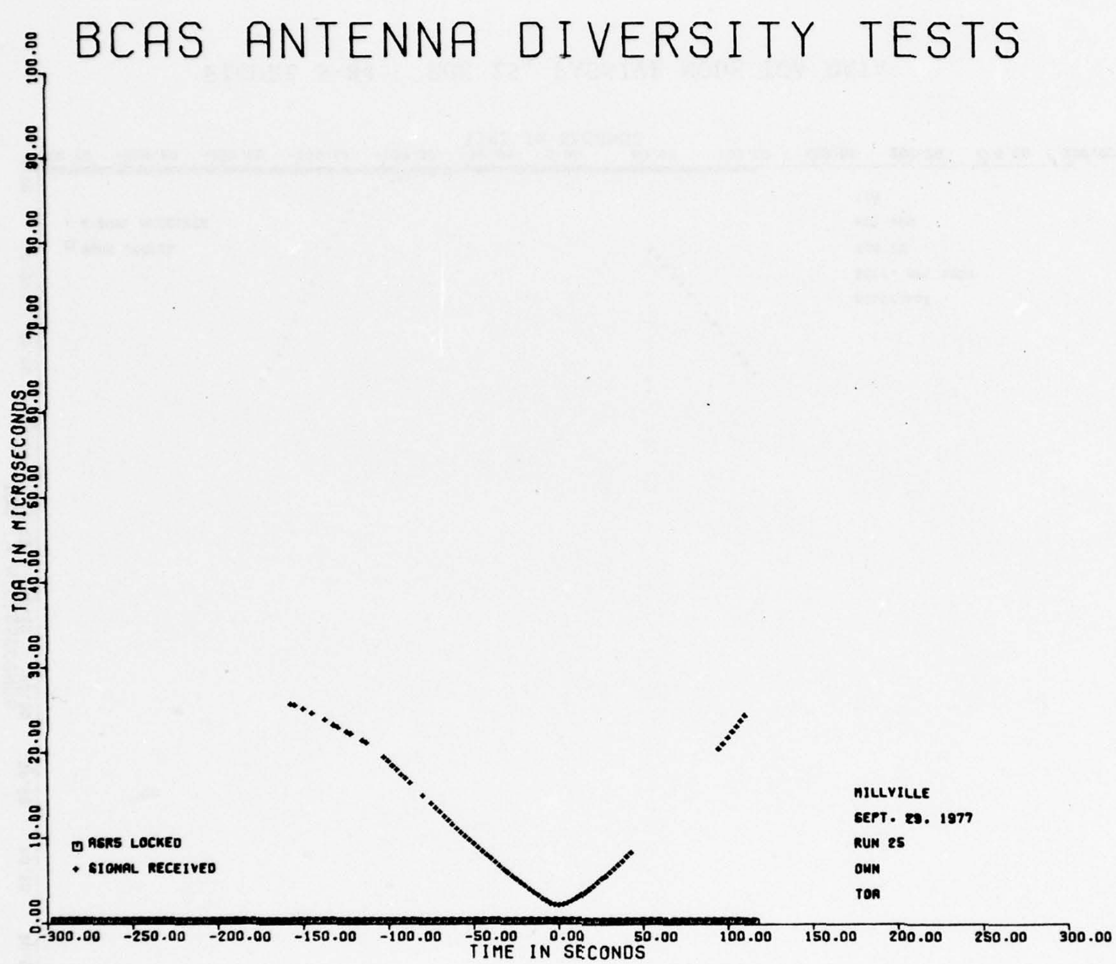


FIGURE 5-83. RUN 25, ACTIVE MODE TOA DATA

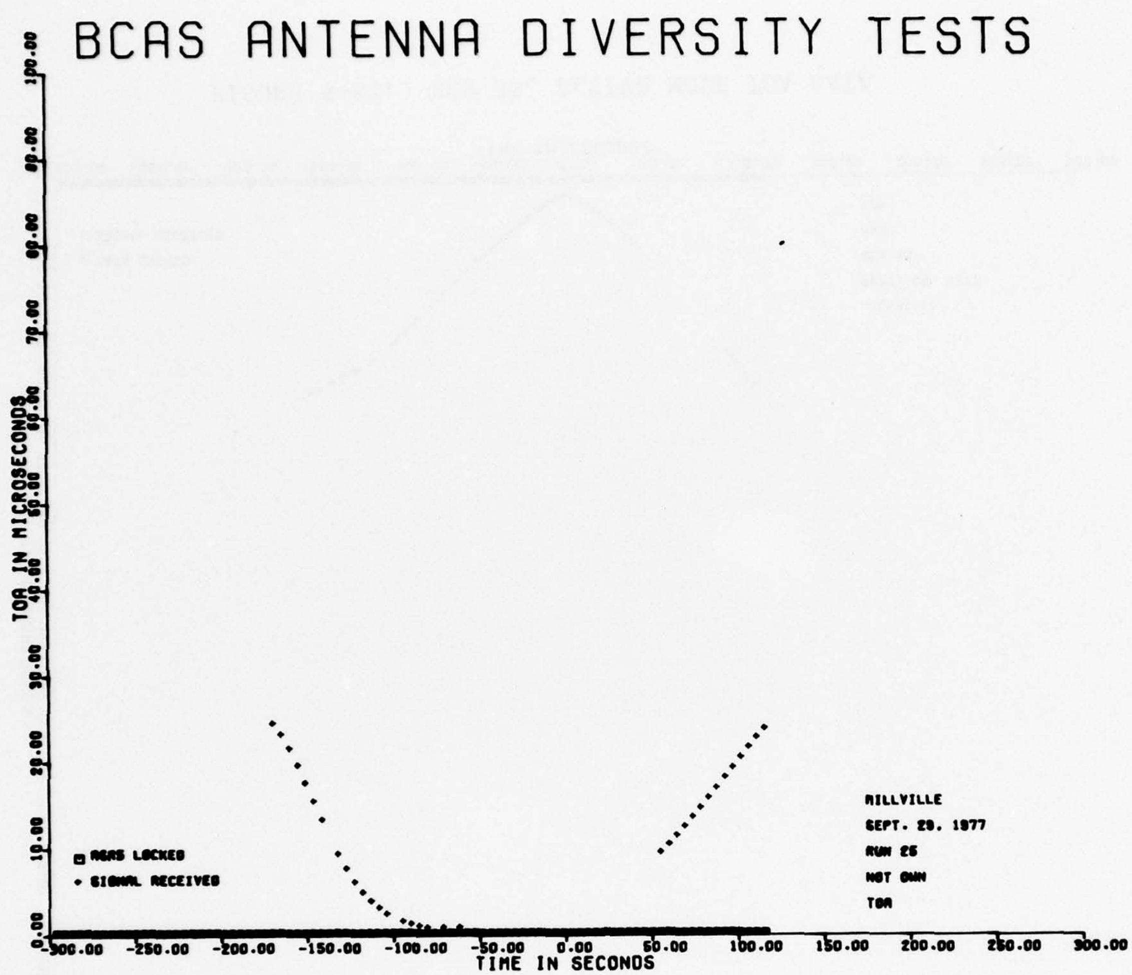


FIGURE 5-84. RUN 25, PASSIVE MODE TOA DATA

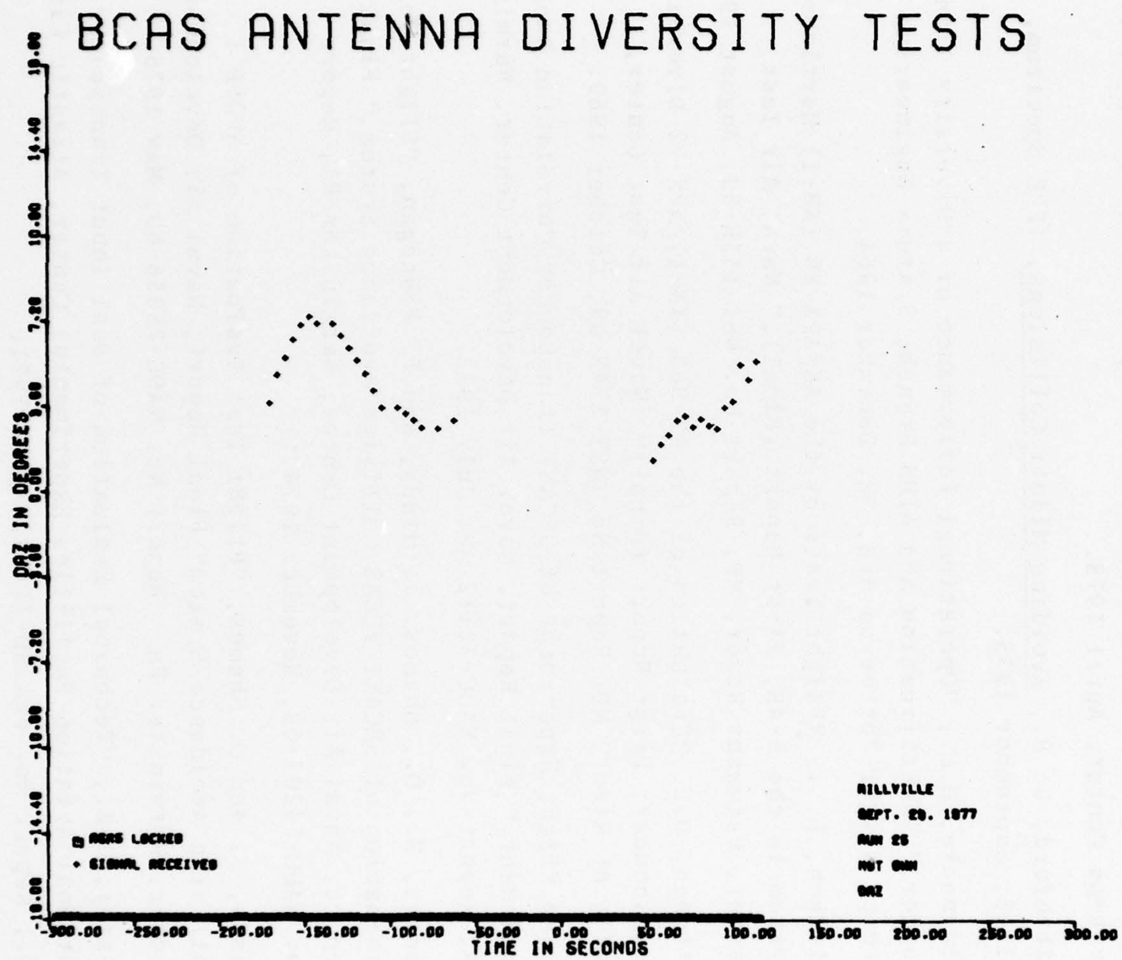


FIGURE 5-85. RUN 25, PASSIVE MODE DAZ DATA

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